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AN ENVIRONMENTAL CGE MODEL OF CANADA AND THE UNITED STATES

by

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ABSTRACT

This paper outlines a static, computational general-equilibrium (CGE) model of environment-economy relationships in Canada and the United States, and provides results from simulating the effects of various tax and regulatory policies specifically designed to achieve select environmental objectives. This modelling work is part of a growing body of literature that seeks to investigate the economic and environmental consequences of responding to environmental concerns through the use of economic instruments. Similar efforts using CGE and other types of economic models, each with their own advantages and limitations, are being undertaken in a variety of fora -- at universities, in business, by governments around the world, and in international organizations such as the Organization for Economic Cooperation and Development and the World Bank.

The "environment model" described here includes five common air pollutants of current concern, specifically, nitrogen oxides, methane, volatile organic compounds, sulphur oxides and carbon dioxide -- pollutants associated with the air pollution issues of greenhouse warming, acid deposition and smog. In investigating the longer-term economic and environmental implications of achieving certain of the many emission targets that have been proposed for these pollutants, the environment model is not limited to employing the more usual economic instruments such as fossil fuel taxes and carbon taxes, but can also address relatively unconventional anti-pollution policies including emission charges and standards, and tradeable permit systems. In doing so, the model provides information on the nature and degree of resource reallocations and consumer welfare change that would be necessary to meet exogenously-specified reductions in flow rates of emission. This seems a natural course for investigation: given any particular emission target relating to any given pollutant, which economic instrument of those feasible is the most cost effective in attaining the goal and how does the use of that economic instrument affect the economy in aggregate and sectorally?

In the environment model, alternative policies to achieve an emission target induce agents to substitute away from more-polluting inputs (notably fossil fuels) in production and consumption, to limit the production of inherently polluting products and to invest in emission-control technologies if the technologies are available and are cost efficient. Importantly, the emission rates of all air pollutants included in the model are consequently altered. The model provides a disaggregate description of the major energy sources and polluting activities in both Canada and the United States, and is able to describe such endogenous, optimizing behaviour in considerable detail.

Simulations designed to address the environmental objective of controlling emissions of carbon dioxide in Canada in line with internationally proposed targets indicate that meeting these targets involves real income costs. The environment model allows the lowest income cost options in achieving the same targets to be identified. In particular, the simulations show that:

i) a carbon tax is more cost effective than either a fossil fuel tax or regulatory emission standards;
ii) appropriate market instruments are more cost effective than emission standards, although regulatory standards can outperform poorly-designed market instruments; and
iii) the rate of carbon tax and associated decline in real income are increasing functions of the carbon dioxide emission target.

Model results for reducing aggregate emissions of sulphur oxides in Canada in rough accordance with the overall target set out in federal-provincial agreement reinforce the finding that market instruments are generally more cost effective than regulatory constraints. In addition, they illustrate that market instruments, in contrast to regulations, encourage industries to adopt all available technologies for reducing pollutant emissions. The use of capital abatement technologies in these simulations is also shown to dramatically alleviate adverse substitution and output effects that would otherwise occur in industries for which they are economically feasible alternatives.

While the model simulations highlight the importance of CGE models in capturing, and quantifying, the impact of a policy change on all sectors of an economy, they also reveal the important interaction of any single policy on all air pollutants. In pursuing a particular environmental policy objective, it is demonstrated that:

i) a single economic policy instrument can succeed in significantly, although indirectly, achieving multiple environmental objectives;
ii) larger complementary effects arise from meeting more demanding environmental targets, but are not equi-proportional; and
iii) different environmental policies can exert very different complementary effects on pollutant emissions.

RÉSUMÉ

Ce document fait état d'un modèle d'équilibre général, calculable (ÉGC) et statique decrivant les liens entre l'environnement et l'économie pour le Canada et les États-Unis. Il présente également des résultats de simulations concernant les effets de différentes taxes et réglementations spécialement conçues pour atteindre certains objectifs écologiques. Ce travail de modélisation fait partie d'une littérature de plus en plus abondante qui cherche à déterminer les conséquences économiques et écologiques d'utiliser des instruments économiques pour répondre aux préoccupations sur la degradation de l'environnement. Des efforts similaires, utilisant des modèles ÉGC et d'autres types de modèles économiques, chacun avec ses propres avantages et limites, ont été entrepris dans une variété d'endroits -- dans les universités, dans le milieu des affaires, par les gouvernements autour du monde et dans les organisations internationales telles que l'Organisation de Coopération et de Développement Économique et la Banque Mondiale.

Le «modèle de l'environnement» peut servir à l'examen de cinq polluants atmosphériques dont on se préoccupe actuellement, à savoir les oxydes d'azote, le méthane, les composés organiques volatiles, les oxydes de soufre et le dioxyde de carbone -- ces polluants sont associés au réchauffement dû à l'effet de serre, aux pluies acides et à la concentration d'ozone troposphérique (smog). En cherchant les répercussions économiques et écologiques à long terme relatives à l'atteinte de certains des objectifs qui ont été proposés pour ces polluants, le modèle n'est pas limité aux instruments économiques les plus usuels tels que les taxes sur les combustibles fossiles et les taxes sur le carbone, mais il donne également accès à des politiques relativement non conventionnelles telles que la tarification et le contrôle des émissions et l'implantation de droits échangeables. Ainsi, il nous fournit des informations liées à la nature et au degré de réattribution des ressources et du bien-être des consommateurs induites par la réduction des débits d'émission conformément à certains objectifs. Ceci semble être une avenue de recherche naturelle: étant donné un objectif écologique particulier, quel est l'instrument économique parmi ceux disponibles qui minimise les coûts associés à son atteinte et quelle est l'effet de l'utilisation de l'instrument économique sur l'economie, au niveau agrégé et sectoriel?

Dans le modèle, les différentes politiques visant à atteindre un objectif écologique incitent les agents à remplacer les produits plus polluants (notamment les combustibles fossiles) utilisés dans les domaines de la production et de la consommation, à limiter la fabrication de produits foncièrement polluants et à investir dans des techniques de contrôle des émissions lorsqu'elles sont disponibles et pas trop coûteuses. Il est important de signaler que tous les débits de polluants atmosphériques sont par conséquent modifiés. Le modèle fournit une description désagrégée des principales sources d'énergie et d'activités polluantes au Canada et aux États-Unis, et peut décrire en détail les différents comportements endogènes et optimisant des agents.

Les scénarios choisis pour simuler le contrôle des débits de gaz carbonique au Canada selon les objectifs proposés au niveau international indique que l'atteinte de ces objectifs comporte des coûts réels en terme de revenu. Le modèle de l'environnement permet d'identifier l'option la moins coûteuse. Les simulations indiquent que:

i) une taxe sur le carbone est moins coûteuse qu'une taxe sur les combustibles fossiles ou qu'une norme sur le rendement;

ii) les instruments de marché appropriés sont moins coûteux que les normes sur le rendement, quoique l'approche réglementaire peut être superieure à un instrument de marché mal conçu;

iii) le taux d'une taxe sur le carbone ainsi que la perte de revenu reel sont des fonctions croissantes de la réduction des débits de gaz carbonique.

Les simulations concernant la réduction des émissions totales d'oxydes de soufre au Canada, conformément avec l'objectif établi dans l'accord fédéral-provincial, confirment que les instruments de marché sont généralement moins coûteux que la réglementation. En plus, elles illustrent que les instruments de marché, contrairement à la réglementation, encouragent les industries à adopter toutes les technologies disponibles pour réduire les émissions polluantes. Ces simulations démontrent également que l'utilisation des technologies de contrôle de la pollution, lorsqu'elles constituent un choix économiquement viable pour les industries, atténue dramatiquement les effets indésirables sur la composition et le niveau de la production.

Tout en soulignant l'importance des modèles ÉCG pour quantifier l'impact d'un changement de politique sur tous les secteurs de l'économie, les simulations démontrent l'importance des interactions d'une politique centrée sur un objectif unique sur tous les polluants de l'air. En poursuivant un objectif écologique précis, il est démontré que:

i) un seul instrument économique peut réussir significativement, même si c'est de maniere indirecte, à atteindre plusieurs objectifs écologiques;

ii) les effets complémentaires augmentent si l'objectif écologique est plus élevé, mais pas de manière directement proportionnelle;

iii) différentes politiques environnementales n'ont pas nécessairement les mêmes effets complementaires.

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1. Introduction

Awareness of and concern over the environmental has grown dramatically over the past decade to the point where there is now a very substantial amount of effort being devoted to understanding its science and its economics. These efforts are international in scope -- they are being undertaken at universities, in businesses and in governments around the world, and in international organizations such as the Organization for Economic Cooperation and Development and the World Bank.

This paper outlines a computational general-equilibrium (CGE) model of environment-economy relationships in Canada and the United States, and provides results from simulating the effects of various tax and regulatory policies specifically designed to achieve select environmental objectives. This work is in line with the growing literature on environment that seeks, through the use of the economic modelling framework, to investigate and to better understand the economic and environmental consequences of responding to environmental concerns through the use of economic instruments. Alternative types of economic models employed in these investigations include CGE models, macroeconomic models and demand-supply models of the energy sector; each approach possesses unique advantages and limitations over the others. (Some of the advantages of employing the CGE approach to environmental modelling are listed in the box on the following page.)

Summary information on the structure of the "environment model" described in this paper is provided in table 1. The model can be conceptualized as consisting of two parts: a traditional static CGE component and an environmental component. The economic component explicitly represents economic behaviour of producers and consumers in Canada and the United States while income and economic activity in the rest of the world are assumed to remain unchanged by Canadian and U.S. policy actions. Sufficient sectoral detail is included to identify the major industrial and residential sources of five common air pollutants of current concern, specifically, nitrogen oxides, methane, volatile organic compounds, sulphur oxides and carbon dioxide. Pollutant emissions arise from both fossil fuel use and industrial processes, and are associated with air pollution issues of greenhouse warming, acid deposition and smog.

The CGE Approach to Environmental Modelling

Analyzing and quantifying the impacts on an economy of a major structural initiative such as environmental protection requires a comprehensive analytical framework that takes into account the complexities of a large number of commodities and commodity prices, a multitude of economic agents and their interactions, and a variety of pollutants. A computable general-equilibrium (CGE) environment-economy model can provide such a framework. This type of economic model consists of a set of mathematical equations that can summarize the functioning of an economy consistent with neoclassical economic theory, and can highlight important interactions between the economy and the environment.

CGE models are appropriate tools for analyzing issues of a longer-term nature, such as the environment, for a number of reasons. These models depict economic interrelationships at an economy-wide level in a way that allows an economy to adapt completely to environmental policy changes, once those changes have been fully implemented. CGE models are designed with the explicit objective of determining efficiency effects of changes in structural policies and can have considerable sectoral detail which is essential in capturing resource reallocation effects resulting from such changes. Thus, they can be used to examine the longer-term impact of relative price changes on resource allocation (factors of production, industry outputs, consumer demands and trade) and overall real income for an economy -- information that is not available from macroeconomic models or input-output models. Given their focus on efficiency, CGE environment-economy models can be well-suited to analyzing the economic costs of meeting a range of environmental targets using alternative economic instruments. In doing so, they can also take account of the effect of pollutant-abatement technologies and can assess the ability of a single economic instrument to achieve multiple environmental objectives.

Environmental policy options in the model include market instruments, non-market instruments and mixed instruments. In terms of market instruments, the model can simulate the effects of various taxes on fossil fuels[1], carbon taxes (a special type of fossil fuel tax in which the rate of tax varies in proportion to the pollution content of fuels) and emission charges. In terms of non-market instruments, quantitative emission standards (industry-specific and industry-wide) are included. For mixed instruments, tradeable permit systems among industries are represented.

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[1] Fossil fuels in the model consist of coal, natural gas (including liquified petroleum gases), motive fuels and non-motive fuels. Motive fuels are an aggregate of motor gasoline, diesel fuel oil, aviation gasoline and aviation turbo fuel. Non-motive fuels are an aggregate of petroleum coke, kerosene, and light and heavy fuel oils.

Table 1
Summary of the CGE Environment-Economy Model Structure

The Economic Component	The Environmental Component

General:
- single-period model: no capital accumulation through saving
- three regions: Canada, the U.S. and the rest of the world
- not a world GE model: rest of world not explicitly modelled
 	
Production Structure:
- 17 industries producing 18 commodities using labour, capital, 7 sector-specific resource factors and 18 intermediate inputs
- labour and capital are homogeneous and mobile between industries
- substitution possible between capital, labour and resource inputs, and between domestic and foreign intermediate inputs
 	
Final Demand:
- an aggregate of consumption and investment
- dependent on income and relative prices
- 1 consumer in each region: excess demands for goods (and capital) accommodated by the rest of the world
 	
Government:
- provision of government services part of service industry
- indirect taxes, tariffs and subsidies included
- net government revenue redistributed to consumers in a non-distortionary manner
 	
Foreign Trade Sector:
- capital is perfectly mobile among regions at the constant world rental rate
- prices for certain resource commodities and all commodities produced in the rest of the world are exogenous
- all other domestic commodity prices adjust to equilibrate a region's merchandise trade balance with its service payments on imported capital
	Scope:
	- air pollution issues of greenhouse warming, acid deposition and smog
	- 5 pollutants modelled: nitrogen oxides, methane, volatile organic compounds, sulphur oxides and carbon dioxide
	
	Pollutant Emissions:
	- arise from the combustion of fossil fuels (in both stationary and mobile sources) and from industrial processes
	- occur in fixed proportion to the levels of polluting intermediate use, polluting production and polluting consumption
	
	Pollution Reduction:
	- substitution among relatively "dirty" fuel inputs
	- decreased production in polluting industries
	- application of "abatement capital" to reduce emissions from the use of a given fuel or industrial process
	
	Economic Instruments for Pollutant Control:
	- air pollution taxes:
	  - various taxes on fossil fuels at uniform rates or at rates proportional to the emission of air pollutants (e.g., a carbon tax)
	  - emission charges
	- quantitative emission standards -- economy-wide and industry-specific
	- tradeable permit systems among industries

The environment model is specifically used here to evaluate longer-term economic and environmental implications of achieving, through the use of economic instruments, certain of the many emission targets that have been proposed for the five air pollutants.[2] In particular, the model is used to provide information on the nature and degree of resource reallocations and real income change that would be necessary to meet exogenously-specified reductions in flow rates of emission. This seems a natural course for investigation: given any particular emission target relating to any given air pollutant, which economic instrument of those feasible is the most cost effective in attaining the goal and how does the use of that economic instrument affect the economy in aggregate and sectorally?

By altering relative commodity and factor prices, alternative policies to achieve an emission target induce agents to substitute away from more-polluting inputs (notably fossil fuels) in production and consumption, to limit the production of inherently polluting products and to invest in emission-control technologies if the technologies are available and are cost efficient. Flows of all air pollutants are consequently altered. The environment model provides a disaggregate description of the major energy sources and polluting activities in both Canada and the United States and is able to describe such endogenous, optimizing behaviour in considerable detail. As such, the model also acts to bridge the gap between partial-equilibrium models of the energy sector which examine emissions from fuel use, and traditional CGE models which do not deal with air pollutant emissions.

Environmental degradation resulting from the activities of individuals or firms may adversely affect other economic agents without the damaging parties having to consider the costs that they impose on others. From an economist's perspective, such an externality causes the market mechanism to fail to allocate a society's scarce resources in an efficient manner. Damaging parties need to be provided with the correct incentive to account for the social costs of their activities and, thereby, to adjust their activities to

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[2] To assess the effects of these structural changes on economic and environmental behaviour and performance, the environment model is simulated both with and without the assumption of the policy change(s) under consideration. Impacts on key economic variables such as real income and real output, and key environmental variables such as pollutant emissions, are then measured by comparing values generated by the policy change to corresponding base-year values.

equate the marginal economic cost with the marginal economic benefit of environmental protection for society as a whole.

For various reasons, however, estimates of the economic benefits of a cleaner environment (or reductions in economic damages) are not presently available. This is directly attributable to the large degree of scientific and economic uncertainty that presently exists over the extent to which anthropogenic emissions contribute to environmental problems and the economic implications of environmental changes. Uncertainty exists in a number of forms including:

- scientific uncertainty in measuring atmospheric emissions;
- scientific uncertainty concerning the extent to which atmospheric emissions, which are flows, contribute to the atmospheric concentration or stock of pollutants;
- scientific uncertainty in predicting the environmental implications of increased stocks of pollutants in the atmosphere;
- economic uncertainty stemming from a lack of understanding of how the environment affects economic activities;
- economic uncertainty in predicting the response of economic agents to policies that are introduced to alleviate atmospheric emissions; and
- economic uncertainty in deciding which policy is the most cost effective and how stringent that policy should be.

As a consequence of inadequate information being available on the economic benefits of environmental protection, the environment model includes only the link from the economy to the environment; the reverse link from the environment to the economy does not exist. The omission of environmentally-induced benefits in the model has two very important implications. First, the model cannot handle issues related to sustainable development which require information on stock variables such as the quality of the environment. Like most CGE models, the environment CGE model only deals with pollutant emissions, which are flow variables. Second, we are able to comment only on the cost effectiveness of economic policies to achieve specific emission targets, and not on whether or not any particular emission target *per se* is optimal. In the absence of adequate information on environmental benefits, it is, therefore, an analysis of environmental targets, alternative economic instruments to achieve them, and the economic

and environmental implications of doing so to which we have directed our attention. The CGE framework provides a very useful way in which to rank economic instruments in terms of their cost effectiveness despite the inherent environmental uncertainties.

Before proceeding further into the paper, a few caveats concerning CGE models and their application to environmental issues need to be mentioned. First, the perspective of CGE models is inescapably directed towards the longer-term when all markets clear. Consequently, these models are unable to comment on transitional (or short-term) issues and costs which may not be insignificant. Second, assumptions underlying the environment model (for example, perfect information, zero administration, compliance and monitoring costs, and constant returns to scale in the production and emission functions) may prejudice the model results somewhat to the extent that these basic tenets are violated in reality. Third, the focus of the model and of this paper is on the implications of using economic instruments to achieve environmental objectives. To the extent that other policy objectives exist and are pursued, the model results may be altered.

The plan of the paper is as follows. Section 2 details the structure of the economic component of the model, dealing in turn with production, consumption and international trade relationships. Section 3 outlines the environmental component, with particular attention to modelling of emissions production, and firms' optimal responses to anti-pollution policies. Section 4 presents illustrative results from simulating policies designed to reduce emissions of carbon dioxide and sulphur oxides in Canada. Section 5 provides some concluding remarks. A list of the model's equilibrium conditions and important identities, together with a guide to the algebraic notation used in the paper, is found in appendix A. Appendix B includes information on data sources (input-output and emissions), on procedures used for estimating capital costs of emission abatement technologies, and on certain key elasticity parameters employed in the environment model.

2. Economic Structure of the Model

In this section, the basic features of the economic component of the environment model are elucidated. Subsections 2.1 to 2.3 provide a description and an algebraic specification of model identities, equations and equilibrium conditions in production, final demand and international trade, respectively.

The environment model is a static CGE model in the Shoven-Whalley tradition.[3] It divides the world into three separate regions, two of which -- Canada and the United States -- are endogenous to the model, with factor prices, demands and supplies adjusting to maintain equilibrium in all markets. The rest of the world (ROW) is modelled exogenously, and serves as a mechanism for specifying demands for imports to and exports from Canada and the United States. In each endogenous region there are 17 industries, each producing a single composite commodity.[4] These industries have been chosen so that each of the most polluting inputs and outputs in the North American economies is identified separately. Factors of production include labour, capital, natural resources in the resource and electric utilities industries, and intermediate materials. Factors are substitutable in response to changes in their prices. Labour and capital are mobile across sectors. In each region, a single aggregate consumer is used to represent final demands for consumption and investment goods. Government expenditures on goods and services, although treated as final demand in the input-output accounts, are treated as a productive activity in the model, and are subsumed within the services industry. Government revenues from environmental taxes and charges, net of subsidies, are given back to the consumer as a lump-sum transfer.

Two different approaches to the nature of international trade are taken in the model. For most commodities, it is assumed that agents differentiate among products on the basis of their national origins; this approach is generally known as the Armington (1969) assumption in the CGE literature. But for some commodities, chiefly the traded primary resource products, the traditional Heckscher-Ohlin formulation is employed, implying that

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[3] Indeed, the model is based on Fortran code for Whalley and Trela's (1986) Canadian Regional Model.

[4] The exception is petroleum refineries, which produce motive fuels and other refined petroleum products as two separate commodities.

producers and consumers in the endogenous regions are price-takers at the fixed world prices of these commodities. Since the model allows one to specify either of these assumptions for each industry, the sensitivity of results to a particular assumption can be investigated.

In the base version of the model, capital is assumed to be mobile internationally, and in perfectly elastic supply to the North American economies. Consequently, its price is fixed throughout the simulations, and net capital flows between North America and the ROW are set to ensure markets clear in each country. There exists the possibility, however, of choosing capital to be internationally immobile, in which case supplies are fixed in each country and capital prices adjust to equilibrate markets. In either case, the model is closed by assuming that either capital prices or capital demands adjust to set the value of service payments (receipts) for imported (exported) capital equal to the balance of trade in commodities. This rule yields an overall balance of payments equilibrium.

2.1 Production

Industrial production in Canada and the United States has been divided into 17 separate industries, each employing a different production technology.[5] The disaggregation chosen allows the analysis to focus on the most fuel-intensive industries (such as electric utilities, transportation, and iron and steel production) and the most polluting industrial processes (such as pulp and paper for carbon dioxide emissions, and non-ferrous smelting for sulphur oxide emissions), as well as affording detailed examination of the energy sector itself, which is modelled as four industries producing five commodities.

Production functions specify the way in which 9 primary factors (labour, capital and 7 sector-specific natural resources[6]) and 54 intermediate inputs (18 commodities, of which 4 are homogeneous, from each of 3 regions -- Canada, the U.S. and the ROW) combine to produce the output of each industry. Demands for each input are determined in the

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[5] Industry sectors in each country (or region) are agriculture, fishing, forestry, coal mining, non-coal mining, crude oil and natural gas, light manufacturing (food and beverage, tobacco, rubber and plastic products, textile, clothing and furniture industries), pulp and paper (including sawmills), iron and steel, non-ferrous smelting, motor vehicles, refineries, chemicals, other manufacturing, electric utilities, transportation and services.

[6] One for each of the model's 6 resource industries as well as for electric utilities.

model as the solution to a cost-minimization problem for each industry. Production in each industry is described by a series of nested constant elasticity of substitution (CES) functions of the primary and intermediate inputs, with the two aggregates combining in a Leontief (fixed coefficients) function at the top level to comprise industry output. Each of the functions is positive-linear homogeneous in its arguments and weakly separable from other aggregates within the function. In other words, the level of output is taken to be a Leontief function of the major aggregates; these aggregates are in turn CES functions of various sub-aggregates, which are CES functions of lower level sub-aggregates, and so on. Including commodity imports, there are six levels of nests in each production function in all; this structure (excluding imports -- see figure 4) is depicted in the schematic of figure 1.

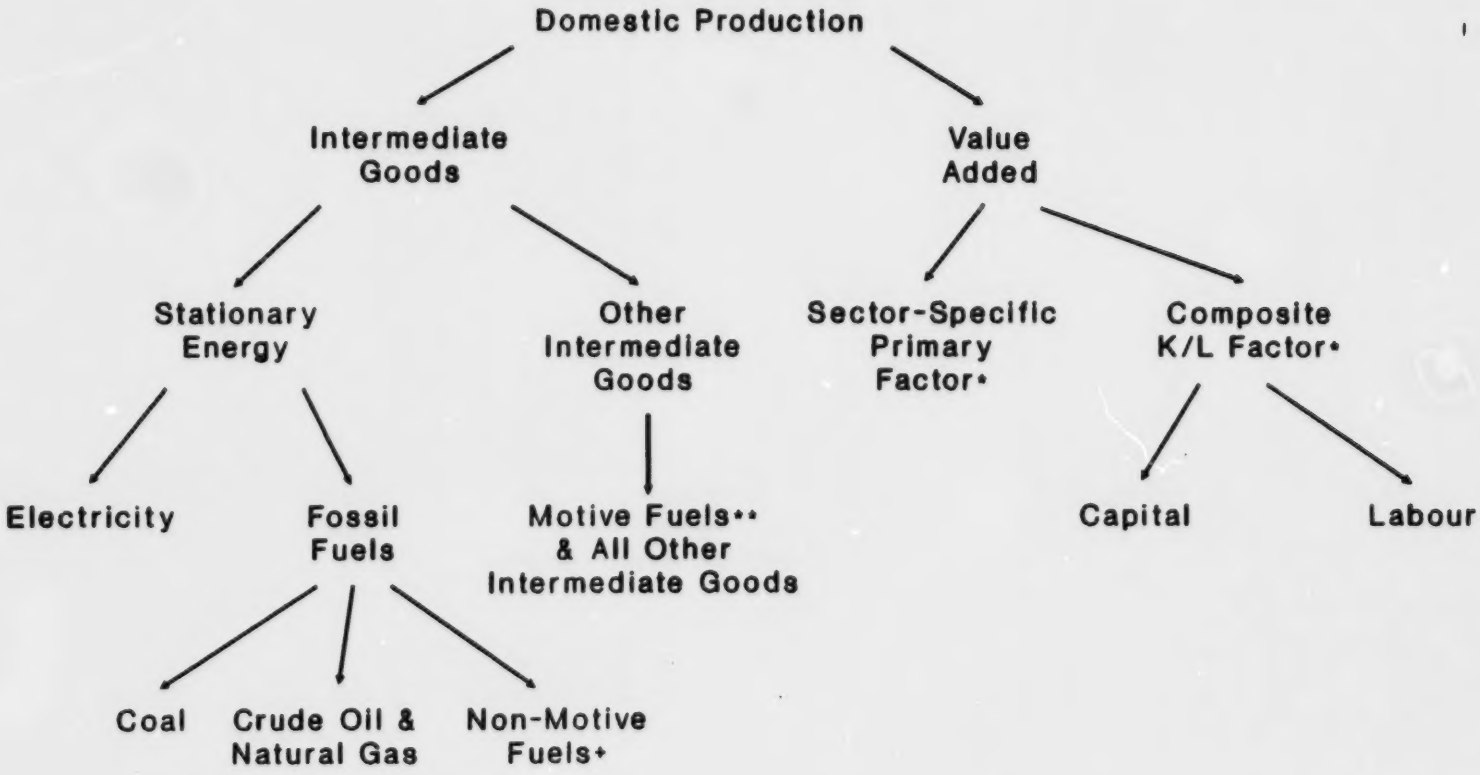
The production structure tends to be awkward in appearance, but relatively simple in implementation. One advantage lies in the fact that it describes input substitution possibilities with a relatively small number of parameters, facilitating calibration and model solution. At the same time, the nesting structure also introduces greater flexibility than a simple CES function, and hence allows more own- and cross-price elasticities of demand to be specified independently. The simple CES function is extremely "parsimonious", requiring only one parameter to describe the curvature properties of the function; this implies, however, that the Allen-Uzawa substitution elasticities for all pairs of inputs in the function are equal. Nesting CES functions within each other introduces more substitution parameters, thereby allowing more elasticities to be specified independently. At a more intuitive level, the structure depicted in figure 1 implies that goods that are grouped together in a nest are closer substitutes for each other than for goods in other nests.

At the first level of nesting in production for both Canada and the United States, gross output of industry i (Y_i) is a Leontief function of intermediate-materials ($X_i^{k,m}$) and value-added ($V_i^{d,n}$) aggregates:

$$(2.1) \qquad Y_i = \min_{X_i^{k,m},\, V_i^{d,n}} \{X_i^{k,m}/a_{xi},\ V_i^{d,n}/a_{vi}\} \qquad \begin{array}{l} i \in I \\ m = n = 2 \\ k \in G_m \\ d \in F_n \end{array}$$

Figure 1

Production Structure of the Environment Model



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* Level of nesting applicable only to resource industries.
** Motor gasoline, diesel fuel oil and aviation fuels.
+ Kerosene, light and heavy fuel oils, and petroleum coke.

where α_{xi} is the intermediate-materials requirement per unit of output i, α_{vi} is the value-added requirement per unit of output i, m is the level of nesting in production corresponding to intermediate materials, n is the level of nesting in production corresponding to value added, I is the set of all industries, G_m is the set of aggregates of commodities in level m, F_n is the set of aggregates of primary factors in level n. The two aggregates, $X_i^{k,m}$ and $V_i^{d,n}$, are in turn multi-level CES aggregates of their corresponding productive inputs. The construction of the materials and value-added aggregates is each described in turn.

In the design of the materials aggregate, an attempt has been made to isolate energy goods to the extent possible, implying greater freedom in the specification of energy demand elasticities, which tend to be important determinants of the results of environmental policy simulations.

At the second level of nesting in production, industries may substitute between what is termed "stationary" energy (i.e., excluding motive fuels) and other inputs (including motive fuels). At the third level, stationary energy is composed of electricity and "stationary" fossil fuels; the other inputs aggregate is a symmetric CES function of all non-energy goods, plus motive fuels. At the fourth level, industries may substitute among the three goods -- coal, crude oil and natural gas and non-motive fuels -- that comprise the "stationary" fossil fuels aggregate. At the fifth level, industries may substitute among domestic and imported products. At the sixth level, substitution is allowed among commodities imported from the U.S. and from the ROW.[7]

The intermediate-materials aggregate for industry i can be formulated as follows:

$$(2.2) \qquad X_i^{k,m} = \left[\sum_j \gamma_i^{j,m} \left(X_i^{j,m+1}\right)^{(\sigma_i^{k,m}-1)/\sigma_i^{k,m}} \right]^{\sigma_i^{k,m}/(\sigma_i^{k,m}-1)} \qquad \begin{array}{l} i \in I \\ m = 2,\ldots,6 \\ k \in G_m \\ j \in G_{m+1} \\ \sum_j \gamma_i^{j,m} = 1 \end{array}$$

[7] The fifth and sixth levels of the function are discussed further in section 2.3.

where $\gamma_i^{j,m}$ is the share parameter for intermediate input j in nesting level m, $\sigma_i^{k,m}$ is the elasticity of substitution for intermediate-materials aggregate k in nesting level m of industry i, and G_{m+1} is the set of all commodities or commodity aggregates at nesting level m+1. Given this specification, we can define $X_i^{j,m+1}(m = 6) = X_{ji}$, $j \in C$, where X_{ji} is the demand for commodity j in industry i, and C is the set of all commodities (a subset of G_{m+1}).

As shown in equation (2.3), a similar structure is applied to value added in production, however, the precise specification differentiates between resource industries (namely, agriculture, fishing, forestry, coal mining, other mining, crude oil and natural gas extraction and electric utilities) and other industries. All industries use capital and labour in production; resource industries also employ a sector-specific factor of production which is intended to represent the contribution of natural resources to output.

In all industries, capital and labour combine in a CES aggregator. In non-resource industries, this aggregate comprises all of value added (n = 2), and enters directly in the production function of equation (2.1). In resource industries, the capital-labour aggregate can be substituted with natural resources in a higher level CES function (n = 2, 3), and this composite is an argument of (2.1).

Value added for industry i can be defined as:

$$(2.3) \qquad V_i^{d,n} = \left[\sum_j \delta_i^{j,n} \left(V_i^{j,n+1}\right)^{(\rho_i^{d,n}-1)/\rho_i^{d,n}} \right]^{\rho_i^{d,n}/(\rho_i^{d,n}-1)} \qquad \begin{array}{l} i \in I \\ n = 2,\ 3;\ 2 \\ d \in F_n \\ j \in F_{n+1} \\ \sum_j \delta_i^{j,n} = 1 \end{array}$$

where $\delta_i^{j,n}$ is the share parameter for primary factor j in nesting level n, $\rho_i^{d,n}$ is the elasticity of substitution in value-added aggregate d at nesting level n of industry i, and F_{n+1} is the set of all primary factors or aggregates of primary factors at nesting level n+1. Specifying value added in this way, we can define $V_i^{j,n+1}(n = 3;\ 2) = V_{ji}$, $j \in P$, where V_{ji} is the demand for primary factor j in industry i, and P is the set of all primary factors (a subset of F_{n+1}).

The introduction of a sector-specific resource factor, in fixed supply, in the CES production function implies decreasing returns to scale at the industry level in resource production. The resource factor is assumed to be fully employed by the industry at all times, and to be immobile intersectorally. The return to the factor is calculated as the residual of output price minus unit production costs; this residual rises when industry output increases and falls when the industry contracts. This relationship generates an upward-sloping, inelastic supply curve, whereas non-resource industries have supply curves that are horizontal. The specification of decreasing returns is particularly important for those industries to which the Heckscher-Ohlin model of international trade is applied, as it precludes complete specialization in response to changes in import prices. (The subject of trade specifications is discussed further in subsection 2.3.)

The joint assumptions of homogeneity and weak separability in the production sub-aggregates permit the application of multi-stage optimization techniques to the solution of the industry's cost-minimization problem.[8] This allows the solution to the cost minimization problem to be represented by a cost function (C_i) of the following form:

$$C_i = c_i(\mathbf{q}, \mathbf{w})\, Y_i = [\alpha_{i1}\, c_i^{k,m}(\mathbf{q}) + \alpha_{v1}\, c_i^{d,n}(\mathbf{w})]\, Y_i \qquad (2.4)$$

$i \in I$, $m = n = 2$, $k \in G_m$, $d \in F_n$

$$c_i^{k,m}(\mathbf{q}) = \left[\sum_j (\gamma_i^{j,m})^{\sigma_i^{k,m}} (q_i^{j,m+1})^{1-\sigma_i^{k,m}} \right]^{1/(1-\sigma_i^{k,m})} = q_i^{k,m} \qquad (2.5a)$$

$i \in I$, $m = 2, \ldots, 6$, $k \in G_m$, $j \in G_{m+1}$

$$c_i^{d,n}(\mathbf{w}) = \left[\sum_j (\delta_i^{j,n})^{\rho_i^{d,n}} (w_i^{j,n+1})^{1-\rho_i^{d,n}} \right]^{1/(1-\rho_i^{d,n})} = w_i^{d,n} \qquad (2.5b)$$

$i \in I$, $n = 2, 3; 2$, $d \in F_n$, $j \in F_{n+1}$

[8] Details of the solution algorithm we employ are omitted from the paper.

where $q_i^{k,m}$ is the market price of materials aggregate k at nesting level m, and $w_i^{d,n}$ is the market price of value-added aggregate d at nesting level n. Once again, this specification allows us to define $q_i^{j,m+1}(m = 6) = q_{ji}$, $j \in C$, where q_{ji} is the market price of commodity j. In addition, $w_i^{j,n+1}(n = 3) = w_{ji}$, $j \in P$, where w_{ji} is the market price of primary factor j. The cost function shares the same separability properties in price space as exhibited by the production function in commodity space. (Equation (2.4) is linear in output because the production function is positive-linear homogeneous).

The optimal demands for intermediate commodities ($a_{ji}(\mathbf{p})$) and primary factors ($b_{ji}(\omega)$) per unit of output can then be calculated using Shephard's Lemma.

$$(2.6a) \qquad a_{ji}(\mathbf{p}) = (X_{ji} / Y_i) = \partial c_i(\mathbf{q},\mathbf{w}) / \partial p_j = \alpha_{ji} \{ \prod_m \partial c_i^{k,m}(\mathbf{q}) / \partial q_i^{j,m+1} \} [\partial q_{ji} / \partial p_j]$$

$i \in I$, $m = 2,\ldots,6$, $k \in G_m$, $j \in G_{m+1}$

$$(2.6b) \qquad \partial c_i^{k,m}(\mathbf{q}) / \partial q_i^{j,m+1} = (\gamma_i^{j,m})^{\sigma_i^{k,m}} (q_i^{j,m+1})^{-\sigma_i^{k,m}} [c_i^{k,m}(\mathbf{q})]^{\sigma_i^{k,m}}$$

$i \in I$, $m = 2,\ldots,6$, $k \in G_m$, $j \in G_{m+1}$

where $q_{ji} = p_j (1 + t_{ji})$, p_j is the output price of good j, and t_{ji} is a tax on the use of intermediate factor j in industry i.

$$(2.7a) \qquad b_{ji}(\omega) = (V_{ji} / Y_i) = \partial c_i(\mathbf{q},\mathbf{w}) / \partial \omega_j = \alpha_{vi} \{ \prod_n \partial c_i^{d,n}(\mathbf{w}) / \partial w_i^{j,n+1} \} [\partial w_{ji} / \partial \omega_j]$$

$i \in I$, $n = 2, 3; 2$, $d \in F_n$, $j \in F_{n+1}$

$$(2.7b) \qquad \partial c_i^{d,n}(\mathbf{w}) / \partial w_i^{j,n+1} = (\delta_i^{j,n})^{\rho_i^{d,n}} (w_i^{j,n+1})^{-\rho_i^{d,n}} [c_i^{d,n}(\mathbf{w})]^{\rho_i^{d,n}}$$

$i \in I$, $n = 2, 3; 2$, $d \in F_n$, $j \in F_{n+1}$

where $w_{ji} = \omega_j (1 + \tau_{ji})$, ω_{ji} is the net-of-tax return to primary factor j, τ_j is a tax on the use of primary factor j in industry i.

With the assumption of perfect competition in all markets, one can conclude that, in equilibrium, all industries set their output prices equal to the average cost of production.[9] This generates the typical zero-profit condition, inclusive of taxes, for equilibrium:

$$(2.8) \qquad p_i = \left[\sum_j a_{ji}(\mathbf{p})\, p_j\, (1 + t_{ji}) + \sum_k b_{ki}(\omega)\, \omega_k\, (1 + \tau_{ki}) \right] (1 + t_i^P)$$

$$i \in I$$
$$j \in C$$
$$k \in P$$

where t_i^P is a tax on the output of industry i. This condition has two interpretations. First, industries that sell products to which the Armington international trade assumption applies are assumed to be price-setters, although the industries behave competitively; thus (2.8) states that the output price is set equal to the average cost of production. Second, industries that sell homogeneous (or Heckscher-Ohlin) products, on the other hand, must sell at the fixed world price of the good; in this case, (2.8) is inverted to solve for the price of the residual sector-specific factor as a function of the world price and the other input prices.

The full employment conditions for primary factors of production must also be satisfied for equilibrium to be established in the model. This requires that demands equal supplies ($\bar{V}_j$) for primary inputs.

$$(2.9) \qquad \sum_i b_{ji}(\omega)\, Y_i = \bar{V}_j$$

$$i \in I$$
$$j \in P$$
$$n = 2, 3; 2$$

---

[9] Since the production functions are positive-linear homogeneous, marginal and average costs are equal.

The model solves (2.8) and (2.9) iteratively until a consistent (i.e., equilibrium) set of (intermediate and primary) factor prices, input demands, output supplies and consumer final demands (discussed below) is achieved. At such an equilibrium, demands equal supplies for all commodities and for all inputs in each region. A schematic of the procedure for solving the model is provided in figure 2.

2.2 Final Demand

Final demand expenditures in Canada and the United States are treated as the utility-maximizing demands of a single representative consumer in each country. Personal consumption and investment demands plus changes in business inventories are aggregated and treated as a single purchase. Whereas government current expenditures on goods and services are included among final demands in the input-output accounts, they are treated as productive activity in the model and comprise part of the services industry. This treatment is adopted due to the significant contribution made by government to value added.

The single representative consumer solves a static, one-period maximization problem to determine final demand levels. Since consumption and investment have been added together, saving does not appear explicitly in the model. The consumer's utility function is identical in structure to the intermediate-materials aggregate in production. The final demand structure of the model (excluding exports) is depicted in figure 3. The multi-level CES utility function for the consumer in endogenous region I (U^I) is:

$$(2.10) \qquad U^I = Z^{k,s} \qquad s = 1,\ k \in C_s,\ I \in L^*$$

$$(2.11) \qquad Z^{k,s} = \left[\sum_j \beta^{j,s} \left(Z^{j,s+1}\right)^{(\varepsilon^{k,s}-1)/\varepsilon^{k,s}} \right]^{\varepsilon^{k,s}/(\varepsilon^{k,s}-1)} \qquad \begin{array}{l} s = 1,\ldots,5 \\ k \in C_s \\ j \in C_{s+1} \end{array}$$

where $Z^{k,s}$ is consumption of commodity aggregate k in nesting level s in consumption, $\beta^{j,s}$ is the share parameter for commodity aggregate j in nesting level s, $\varepsilon^{k,s}$ is the elasticity

Figure 2

Procedure for Simulating Environmental Policy Impacts

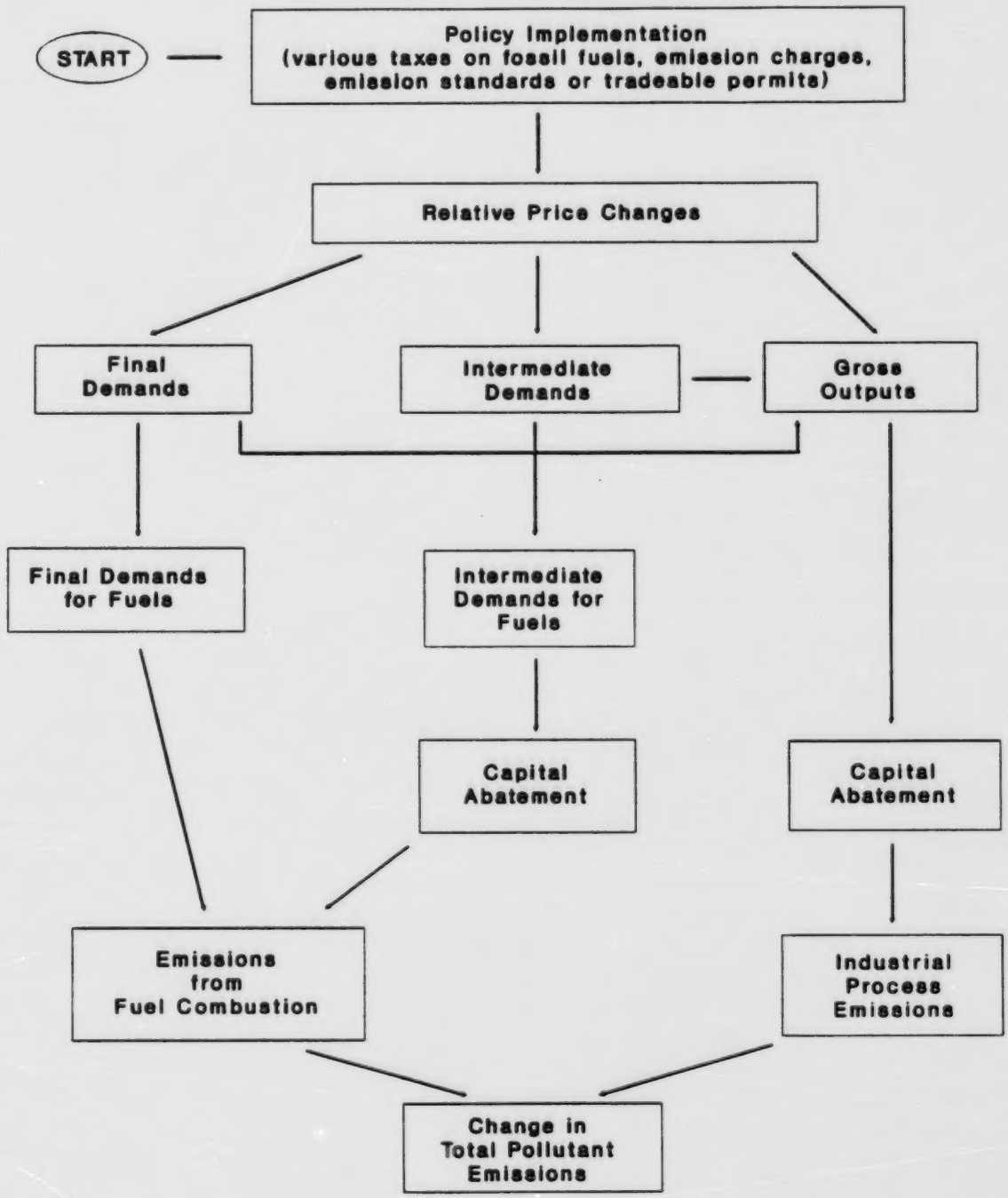
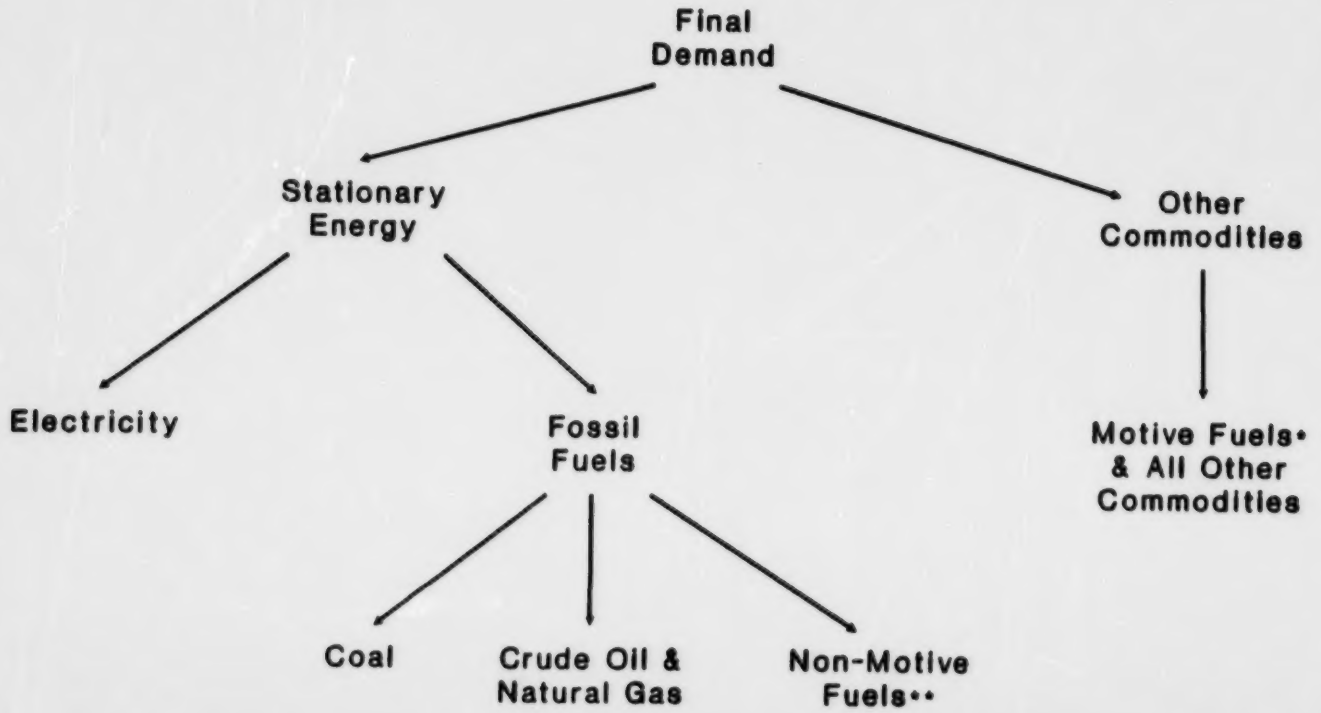


Figure 3

Final Demand Structure of the Environment Model



• Motor gasoline, diesel fuel oil and aviation fuels.
•• Kerosene, light and heavy fuel oils, and petroleum coke.

of substitution in preferences, L^N is the set of endogenous regions (Canada and the United States) in the model, C_s is the set of aggregates of commodities in nesting level s, and $Z^{s+1}(s=5) = Z_j$, $j \in C$, is the final demand for commodity j.

The levels of consumer demands are determined by market prices and aggregate income. Income equals the value of each consumer's endowment of primary factors, plus the excess of government tax revenues over subsidies, which accrues to the consumer as a lump-sum transfer. Although any pattern of property rights can be specified, it is generally assumed that the returns to labour and natural resources accrue wholly to the consumer of the country in which they are employed. Foreign shares of capital income are chosen to ensure a balance of payments (current account) equilibrium in the benchmark data set.

A complete statement of the income-expenditure identity can be found in appendix A.

2.3 Foreign Sector

The environment model can be regarded as a partial world model. The Canadian and U.S. economies are completely endogenous, in the sense that national income, factor prices and output levels are determined internally. In contrast, the income of the ROW is exogenous, and only trade flows between ROW and North America are determined endogenously.

As mentioned previously, two distinct treatments of international trade are employed simultaneously in the model. For some commodities, the traditional Heckscher-Ohlin formulation is adopted, which assumes that all countries produce homogeneous products that must sell in international markets at a uniform world price. The most important implication of this approach is that the domestic price of the good in each country must equal the exogenous world price plus the tariff levied on imports.

For other commodities, we have adopted the Armington approach, which posits that consumers differentiate among products on the basis of their countries of origin. This implies that each country's product can sell at a different price, and the domestic price is

not linked to an exogenous world price. In particular, for these commodities, we employ the "almost small open economy" assumption (Harris, 1988) that Canada and the United States are price-takers for imports, but are price-setters for exports.[10] The structure of substitution among domestic and competing imported goods for the Armington commodities is depicted in figure 4. One implication of this structure is that the elasticity of demand for a country's exports exceeds the elasticity of demand for imports in each other country, since importers are able to substitute between different suppliers as well as between domestic and imported goods.

The decision to employ the two conflicting paradigms simultaneously reflects the fact that neither is completely satisfactory. The deficiencies of the Heckscher-Ohlin formulation are fairly well known: most importantly, it cannot explain the existence of intra-industry trade, which is fairly pervasive, nor the existence of variable price differentials among otherwise identical imported and domestic goods. Moreover, economic models typically deal with broad aggregates, which cannot realistically be taken to be identical, or homogeneous, in all countries.

Although the Armington approach is commonly used in CGE models, it has been widely criticized as unrealistic. In particular, Armington models tend to generate large terms-of-trade effects in trade-policy simulations, swamping allocative-efficiency effects which many economists feel are of greater importance (see Brown, 1987; Shoven and Whalley, 1984). Moreover, when production functions exhibit constant returns to scale, Armington models will display virtually no link between changes in domestic and world prices, which does not seem realistic in the long run.

To our knowledge, the two approaches have rarely been implemented together in CGE models in the past,[11] and so there is little guidance about which approach should be applied to which industry. In the base version of the model, we have chosen to employ the Heckscher-Ohlin approach only for the traded resource products: namely, fishing,

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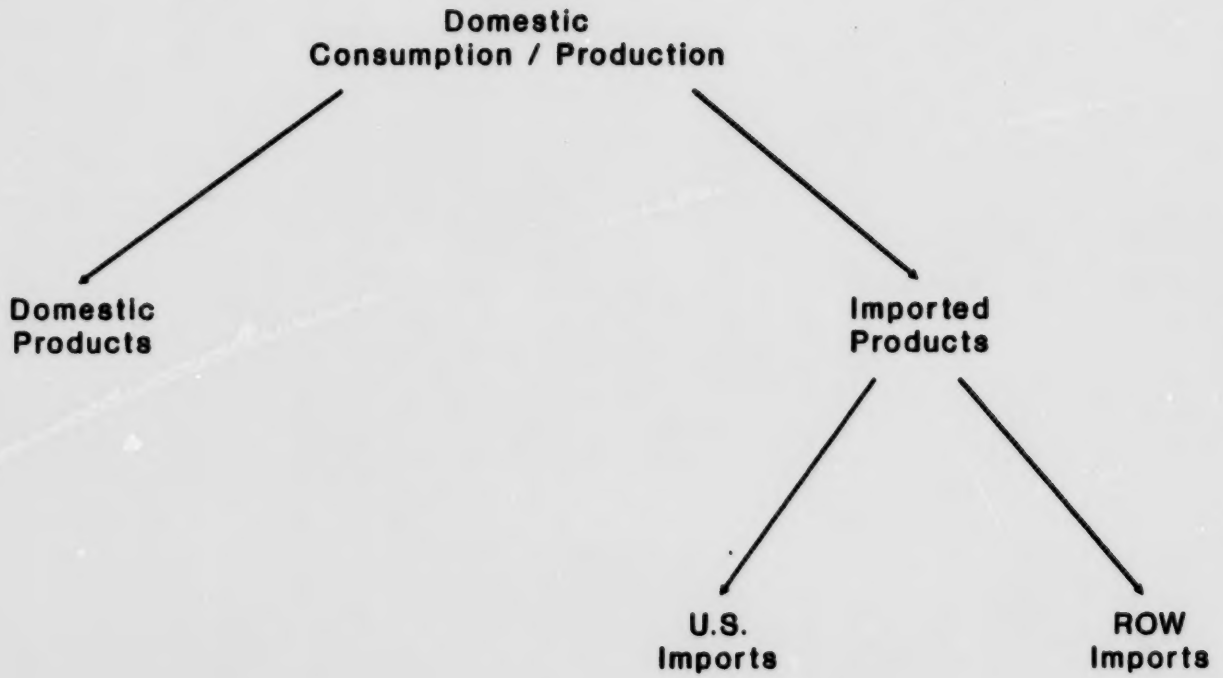
[10] It is assumed that exporters do not exploit this market power, and export prices are set equal to the domestic average cost of production.

[11] See Bergmann (1989) for one example of the simultaneous use of the two assumptions in a CGE model.

Figure 4

Import Structure of the Environment Model•



• Not applicable to homogeneous product industries, i.e., fishing, forestry, crude oil-natural gas, & non-coal mining.

forestry, non-coal mining, and crude oil and natural gas. This would seem to accord with intuition about the nature of trade in these sectors.

Although each country can maintain a surplus or deficit on its trade account, an overall balance of payments equilibrium is required. Real exchange rates are fixed, and balance of payments equilibrium is achieved through adjustments in the terms of trade and in the value of capital imports. This condition is not imposed explicitly in the model, but can be shown to hold as an implication of Walras' law; the balance of payments equilibrium condition is provided in appendix A.

3. Pollution and Abatement

3.1 Pollutant Emissions and "End-of-Stack" Abatement Technologies

The environment model determines how emissions of five air pollutants -- nitrogen oxides (NOx), methane (CH_4), volatile organic compounds (VOC), sulphur oxides (SOx), and carbon dioxide (CO_2) -- vary in response to changes in economic activity. As such, the model accounts for the pollutants which are precursors of several environmental problems of current concern, including smog, acid deposition and greenhouse warming.

In the model, emissions result from the combustion of fossil fuels in intermediate production and final demand, and from some industrial processes which are inherently polluting.[12] The industry aggregation chosen allows the model to identify separately most of the important sources of the five air pollutants in the Canadian economy. We employ the standard assumption that emissions are a linear function of the volume of fuel combustion in each industry and of the levels of output from polluting industrial processes. Thus, for each industry, emissions of a particular pollutant are described by:

$$(3.1) \qquad E_i = \sum_j e_{ji} X_{ji} + e_i^Y Y_i \qquad \begin{array}{l} i \in I \\ j \in C \end{array}$$

where E_i is the quantity of the pollutant emitted, and e_{ji} and e_i^Y are the emission factors (or coefficients) associated with inputs and output, respectively.[13] (Emission factors, e_{ji}, are zero for all commodities other than the four polluting fossil fuels.)

Thus, industries are able to reduce emissions in response to anti-pollution policies by altering the input vector -- substituting towards cleaner fuels and reducing the overall energy-intensity of production -- and by reducing the level of output.

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[12] For example, in the pulp and paper industry, emissions of carbon dioxide from the combustion of spent pulping liquors are separate and distinct from carbon dioxide emissions caused by the burning of fossil fuels. Carbon is also released during the reduction of calcium carbonate in the production of cement, and the derivation of hydrogen from natural gas in ammonia production.

[13] Pollutant subscripts are omitted for convenience.

Industries also have access to abatement technologies, where they exist, which reduce emissions resulting from any given input-output combination. Abatement technologies are modelled as a single, homogeneous capital good (one for each industry and each pollutant) which can be hired by the firm at the rental price of the productive capital good. Each unit of abatement capital results in an equal marginal reduction in pollutant emissions. Thus the marginal cost of abatement is constant, up to some maximum reduction implied by the physical nature of the abatement technology being modelled. In cases where abatement technologies exist, then, (3.1) is modified as:

$$(3.1'') \qquad E_i = \sum_j e_{ji} X_{ji} + e_i^Y Y_i + e_i^A A_i \qquad \begin{matrix} i \in I \\ j \in C \end{matrix}$$

where e_i^A is the (negative) marginal reduction in emissions resulting from investment in abatement capital (A_i).[14]

Given that abatement capital appears as an argument of the emission function but not of the production function, this model is most descriptive of so-called "end-of-stack" technologies which clean emissions without altering production techniques, rather than of more basic process modifications that limit pollution. Fortunately, many of the technologies commercially available to control emissions of SOx and NOx are of the former type. These include flue-gas desulphurization (scrubbers) for SOx, which is used extensively by coal-fired power plants and other large pollution sources. Some process modifications, including installation of low-NOx burners and low-excess-air boilers, for example, have relatively little impact on demands for other inputs, and so (3.1") should offer a reasonable model for these cases as well. Since very limited possibilities presently exist for reducing emissions of CO_2 by means of end-of-stack technologies, these are not included in the model.

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[14] No abatement technologies for final demand emissions are considered. As a result, emissions from final demand activity are governed by:

$$E^l = \sum_j e_j^l Z_j^l \qquad \begin{matrix} l \in L^* \\ j \in C \end{matrix}$$

Firms' decisions to hire abatement capital depend on (3.1") and on the pollution-control policy implemented in the simulation of the model. In the absence of any pollution policy, firms will not invest in abatement, since it is costly but yields no market returns. The response of profit-maximizing firms to different classes of pollution policies is detailed in the following subsection.

3.2 Pollution-Control Policies

The environment model allows for analysis of two classes of pollution-control policies, in addition to traditional taxes on market inputs and outputs (which also affect the level of pollution). These are (i) emission charges, in which a specific tax is levied on the quantity of pollution created by all industries in the economy, and (ii) quantitative emission constraints. Emission constraints may take a number of forms: most simply, a limit can be placed on the quantity of pollution emitted by a particular industry. (We do not consider standards for consumers' emissions, as these are unlikely to be practicable.) Alternatively, the model can be used to compute the (second-best) optimal allocation of limits among all industries (as set by a social planner) which, given the production and emission functions and the average costs of abatement, minimizes the efficiency cost of achieving a given reduction in total industrial emissions. Finally, the model can represent a scheme of tradable emissions permits among industries, assuming that resale markets for permits are perfectly competitive.

As will be seen, each of these policy regimes induces similar changes in economic variables, particularly prices, input demands and output supplies. (It is indicated below that, within the context of the CGE model and its behavioural assumptions, the economic effects of a tradable permits system is identical to the social planner's second-best optimal allocation and to an emission charge, when each is designed to achieve the same emission target.) This similarity is certainly an artifact of the assumptions of perfect information, zero administration, compliance and monitoring costs, and constant returns to scale in the production and emission functions. In practice, some pollution policies are likely to be superior to others in some situations, to the extent that these assumptions are violated in reality. Such considerations, while important, are beyond the scope of the CGE model and of this paper.

The manner in which competitive profit-maximizing firms respond to anti-pollution policies -- through changes in prices, outputs and input demands, and through investment in abatement technologies -- depends on the specific policy being implemented. The general problem of standards, charges and tradable permits is best introduced by considering the case of an industry-specific standard applied equally to all firms in a particular industry.[15] This scenario, while interesting in its own right as a common instrument of anti-pollution policy, will provide the essential framework for the analysis of other policies that follows.

The model outlined here is broadly similar to the analytical work of several authors, including Baumol and Oates (1975), Stevens (1988) and Tschirhart (1985). For a partial treatment of these issues in a CGE model, see Bergmann (1989).

(a) Industry-specific emission standards

The industry-specific standard simply requires each firm not to exceed a given flow rate of pollution, denoted $\bar{E}_i$. In formal terms, the firm's problem is to maximize profits:

$$(3.2) \qquad \max_{X_{ji}} \{p_i Y_i - \sum_{j \in c} q_{ji} X_{ji} - r^A A_i\}, \quad i \in I, \quad \text{subject to}$$

$$(3.2a) \qquad \sum_{j \in c} e_{ji} X_{ji} + e_i^Y Y_i + e_i^A A_i \leq \bar{E}_i \quad \text{and}$$

$$(3.2b) \qquad -(e_i^A A_i) \Big/ \left[\sum_{j \in c} e_{ji} X_{ji} + e_i^Y Y_i \right] \leq \bar{R}_i$$

$$A_i \leq \bar{A}_i$$

$$\bar{A}_i = -\bar{R}_i \left(\sum_{j \in c} e_{ji} X_{ji} + e_i^Y Y_i \right) / e_i^A$$

[15] Given the assumption of constant returns to scale in production, the distinction between firms and the industry is largely spurious. Throughout what follows, we consider the case of a single representative firm in each industry.

and subject to the production function $Y_i = f_i(\mathbf{X}_i)$.[16] In (3.2b), $\bar{R}_i$ represents the maximum feasible percentage reduction in emissions through the purchase of abatement capital.

The first order (Kuhn-Tucker) conditions for optimizing program (3.2) are:

$$(3.3a) \qquad X_{ki}: \quad p_i f_{ki} - q_{ki} - \{ \lambda_i + (\mu_i e_i^A A_i) / [\sum_{j \in c} e_{ji} X_{ji} + e_i^Y Y_i]^2 \}$$

$$(e_{ki} + e_i^Y f_{ki}) \leq 0 \qquad X_{ki} \geq 0 \qquad X_{ki} (\delta L / \delta X_{ki}) = 0$$

$$(3.3b) \qquad A_i: \quad -r^A - \lambda_i e_i^A + (\mu_i e_i^A) / [\sum_{j \in c} e_{ji} X_{ji} + e_i^Y Y_i] \leq 0$$

$$A_i \geq 0 \qquad A_i (\delta L / \delta A_i) = 0$$

$$(3.3c) \qquad \lambda_i: \quad \bar{E}_i - \sum_{j \in c} e_{ji} X_{ji} - e_i^Y Y_i - e_i^A A_i \geq 0 \qquad \lambda_i \geq 0 \qquad \lambda_i (\delta L / \delta \lambda_i) = 0$$

$$(3.3d) \qquad \mu_i: \quad \bar{R}_i + (e_i^A A_i) / [\sum_{j \in c} e_{ji} X_{ji} + e_i^Y Y_i] \geq 0 \qquad \mu_i \geq 0 \qquad \mu_i (\delta L / \delta \mu_i) = 0$$

where f_{ki} represents the marginal product of input k in industry i, λ_i is the Lagrange multiplier associated with constraint (3.2a) -- the price, at the margin, of meeting the target flow rate of emissions, μ_i is the Lagrange multiplier associated with constraint (3.2b), and L is the Lagrangean function for program (3.2). Assuming an interior solution for X_{ki}, equation (3.3a) can be rewritten as:

$$(3.4) \qquad p_i f_{ki} = q_{ki} + \Lambda_i (e_{ki} + e_i^Y f_{ki}) \quad \text{where}$$

---

[16] Primary inputs have been excluded throughout this section for convenience; they can be thought of as implicitly included in the input vector **x**.

$$(3.4a) \qquad \Lambda_i = \lambda_i + (\mu_i \, e_i^A \, A_i) \; / \; [\sum_{j \in C} e_{ji} \, X_{ji} + e_i^Y \, Y_i]^2$$

If constraint (3.2a) is binding at the optimum, λ_i must be positive. Manipulation of the Kuhn-Tucker conditions for optimality yield three possible solutions to program (3.2):

$$(3.5a) \qquad \lambda_i < -r^A / e_i^A \Rightarrow A_i = 0 \text{ and } \mu_i = 0;$$

from (3.4a) we obtain $\Lambda_i < -r^A / e_i^A$

$$(3.5b) \qquad \lambda_i = -r^A / e_i^A \Rightarrow \bar{A}_i \geq A_i \geq 0 \text{ and } \mu_i = 0;$$

from (3.4a) we obtain $\Lambda_i = -r^A / e_i^A$

$$(3.5c) \qquad \lambda_i > -r^A / e_i^A \Rightarrow A_i = \bar{A}_i \text{ and } \mu_i = (\lambda_i \, e_i^A + r^A) \, A_i \; / \; \bar{R}_i;$$

from (3.4a) we obtain $\Lambda_i = [\lambda_i \, (1 - \bar{R}_i) - (r^A / e_i^A) \, \bar{R}_i]$

In each case (3.5a) to (3.5c), the firm reduces emissions by altering the input vector to substitute away from polluting inputs. This causes production costs to rise and, consequently, prices to increase and/or output to decrease. The firm then makes a decision of whether or not to purchase abatement capital in order to achieve the emissions target at least cost.

When (3.5a) obtains, the marginal cost of emission reduction through abatement, $-r^A/e_i^A$, is simply too expensive, and no abatement capital is hired at the optimum. This solution can be seen intuitively in (3.4) where the right-hand side represents the shadow price of the input. This shadow price is the sum of the market price and the "marginal emissions cost" of the input (the cost of emissions, Λ_i, times the marginal contribution of the input to total emissions).

When (3.5b) obtains, the marginal cost of abatement just equals the shadow price of other measures, i.e., substitution to less polluting inputs and output reduction. At this point, the industry buys the quantity of abatement capital that is necessary to meet constraint (3.2a) and, thereby, reduce its costs of production.

When (3.5c) obtains, the marginal cost of emission reduction through abatement is less than the shadow cost of other measures, and the maximum feasible quantity of abatement is hired. Since the "end-of-stack" abatement capital can reduce emissions by the percentage $\bar{R}_i$ for each marginal unit of pollution, the shadow price of emissions is simply an average of the cost of emissions reduction through abatement and the cost of other measures.

This solution is implemented in the model by replacing (3.4) for the normal input demand functions, which are implicitly of the form $p_i f_{ki} = q_{ki}$, $k \in C$. Given the fixed marginal cost of emission reduction through abatement, the equilibrium value of λ_i, for which $E_i = \bar{E}_i$, is determined iteratively.

(b) Tradable emission permits

In the preceding section, the policy under consideration was an industry-specific quantitative constraint on emissions; more often, however, one is interested in controlling the total emissions created by all industries in the economy rather than those of a single firm or industry. In general, it would not be efficient to apply such a global restriction uniformly across all industries, nor to legislate a uniform percentage reduction in emissions by all industries (a generalization of the preceding analysis). Rather, emission reduction should take place in those industries where it is most cheaply effected. In this section, we consider means of achieving such a reduction in emissions.

In particular we consider the effects of a system of emission permits, issued by the government and traded freely among firms in all industries of the economy. These permits may be freely assigned to firms in the initial situation or auctioned off to the highest bidder; barring strategic behaviour on the part of firms, both mechanisms yield the same equilibrium allocation in our model. Emission permits are valuable to polluting firms and so will earn rents in equilibrium. The distribution of the rents does, of course, depend on

the initial assignment of property rights; however, since all such rents are assumed to be earned by the single representative consumer in each country, this issue is of no relevance in the CGE model.

Consider then the problem facing polluting firms (industries) that must purchase emission permits from the government:

$$(3.6) \qquad \max_{X_{ki}, E_i} \{p_i Y_i - \sum_{j \in c} q_{ji} X_{ji} - r^A A_i - \pi \bar{E}_i\}, \quad i \in I, \quad \text{subject to}$$

$$(3.6a) \qquad \sum_{j \in c} e_{ji} X_{ji} + e_i^Y Y_i + e_i^A A_i \leq \bar{E}_i \quad \text{and}$$

$$(3.6b) \qquad -(e_i^A A_i) \; / \; [\sum_{j \in c} e_{ji} X_{ji} + e_i^Y Y_i] \leq \bar{R}_i$$

where π is the market price (identical for all industries) of emission permits. The program (3.6) is, of course, quite similar to that considered in the preceding section. The first-order conditions for an optimum are equally similar except for an additional condition relating to $\bar{E}_i$.

$$(3.7) \qquad -\pi + \lambda_i \leq 0 \qquad\qquad \bar{E}_i \geq 0$$
$$\bar{E}_i \; (\partial L \; / \; \partial \bar{E}_i) = 0$$

Two possible solutions to the maximization problem exist. In the case where $\pi > \lambda_i$, $\bar{E}_i$ must equal zero. This implies that both purchases of polluting inputs and production of polluting outputs are zero. This solution is, however, unrealistic and is not considered in the model.

In the case where $\pi = \lambda_i$, on the other hand, the solution is the same as that of the industry-specific standards program (3.2) except that λ_i is replaced by π. The equilibrium value of π is that which equates firms' demands for permits with government's exogenous

supply: specifically, the value of π that solves $\sum_i \bar{E}_i(\pi) = \bar{E}$. The market price of emissions permits is determined iteratively in the CGE model.

The allocation implied by program (3.6) is in fact a second-best optimal one, in the sense that it minimizes the efficiency loss associated with constraining emissions to some given overall level $\bar{E}$.[17] The existence of this property of tradable-permit schemes can be supported informally by noting that maximization of the sum of all firms' profits subject to the constraint, $\sum_i E_i = \bar{E}$, yields the same first order conditions as program (3.6). Thus solution of the social planning problem gives rise to the same allocation as does the tradable-permit system.

Consequently, simulations involving systems of tradable permits can, given the assumptions of the model, also be interpreted as a set of emission standards assigned among industries with which the planner, acting with full information about emissions and technologies, achieves the optimal allocation of reductions for the economy.

(c) Emission charges

The final pollution-control policy regime to be considered is the emission charge, a specific tax on emissions (denoted θ) levied uniformly on all industries in the economy. The profit-maximization problem in this case is:

$$(3.8) \qquad \max_{X_{ki}} \{p_i Y_i - \sum_{j \in c} q_{ji} X_{ji} - r^A A_i - \theta E_i\}, \quad i \in I, \quad \text{subject to}$$

$$(3.8a) \qquad -(e_i^A A_i) \,/\, [\sum_{j \in c} e_{ji} X_{ji} + e_i^Y Y_i] \leq \bar{R}_i$$

The resolution to this problem yields the same solution as the program given by (3.6) except that the price of emissions π is replaced by the exogenous tax rate θ. Thus,

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[17] This observation has been made by a number of authors, notably Baumol and Oates (1975: 142) and Dales (1968).

the two policies are equivalent in the following sense: an emission charge levied on all firms which induces some flow rate of emissions, say E^*, will have identical effects on prices, outputs and demands as a system of tradable permits for which the total supply of permits is constrained to E^*.

4. Illustrative Simulation Results

Illustrative environment model results are presented in this section for unilateral Canadian action in controlling emissions of carbon dioxide, the pollutant of primary concern with respect to the issue of greenhouse warming, and in controlling emissions of sulphur oxides, precursors to atmospheric sulphuric acid and acid deposition.

4.1 Carbon Dioxide Emission Control

Illustrative simulation results reported in section (a) deal with the relative cost effectiveness of introducing alternative economic instruments in Canada that are designed to meet a specific reduction in carbon dioxide emissions. Model results in section (b) compare economic costs of achieving different CO_2-emission targets using a single market instrument, the carbon tax.

(a) Alternative policies to achieve a specific target

In accordance with the May 1990 Bergen Declaration, Canada is committed to establishing national strategies and/or targets and schedules to limit or reduce carbon dioxide emissions and other greenhouse gas emissions as much as possible and to stabilize them. Canada and most other countries expressed the view that stabilizing these emissions at 1990 levels by the year 2000 must be the first step. This goal for Canada was reaffirmed in December 1990 in *Canada's Green Plan for a Healthy Environment.*

Simulation results in table 2 provide a comparison of economic and environmental impacts of a uniform tax on the price of fossil fuels, a carbon tax and "industry emission standards", each of which is designed to achieve the specific environmental policy objective of stabilizing carbon dioxide emissions at their 1990 levels by the year 2000. Achievement of this emission target means that aggregate carbon dioxide emissions from fossil fuel combustion in Canada must be reduced under each policy scenario by almost 15 per cent of their level otherwise forecast for 2000. The tax base is identical for the fossil fuel tax and the carbon tax; in contrast to the single ad valorem tax rate of the fossil fuel tax, however, ad valorem carbon tax rates differentiate among fossil fuels according to the differing carbon contents of the fuels. For the purposes of this comparison, emission

Table 2

Alternative Economic Instruments to Stabilize CO_2 Emissions at 1990 Levels by 2000[a]
(per cent change except as noted)

	Tax on Fossil Fuels[b]	Carbon Tax[c]	Industry Emission Standards[d]
Real Income[e]	-0.5	-0.3	-0.4
Real GDP at Factor Cost	-0.6	-0.5	-0.8
Terms of Trade Index[f]	1.0	1.0	1.2
Net Capital Imports[g]	-0.2	-0.2	-0.3
Labour Reallocation Index[h]	0.7	0.6	0.7
Output Change:			
Refineries	-19.8	-10.6	-10.4
Iron & steel	-4.4	-8.3	-10.6
Pulp & paper	-2.9	-4.1	-2.2
Transportation	-5.3	-3.3	-7.2
Non-ferrous smelting	-2.6	-3.1	-1.5
Coal mines	-2.7	-2.9	-1.9
Chemicals	-4.8	-2.8	-0.7
Electric utilities	2.3	-2.6	-10.5
Non-coal mining	-3.2	-2.4	-0.8
Fishing	-4.0	-1.9	0.4
Other manufacturing	-0.5	-1.3	-0.4
Motor vehicles	-1.0	-1.2	-1.2
Forestry	-2.8	-1.0	-0.4
Crude oil & natural gas	-3.0	-0.4	0.0
Agriculture	-0.9	-0.4	0.2
Light manufacturing	-0.1	-0.1	0.6
Services	0.4	0.4	0.3
Average - all industries	-1.2	-0.9	-1.0

Table 2 - Continued

(per cent change except as noted)

	Tax on Fossil Fuels[b]	Carbon Tax[c]	Industry Emission Standards[d]
Tax Rate:			
Coal	33.0	140.0	i
Natural Gas	33.0	24.0	i
Motive Fuels	33.0	14.0	i
Non-Motive Fuels	33.0	25.0	i
¢ per litre of gasoline	17.4	7.6	i
Revenues from Policy Measure (1990 $ billions)	13.4	11.2	i
Total Emissions, Canada:			
Nitrogen oxides	-15.3	-11.4	-12.8
Methane	-7.6	-5.8	-5.0
Volatile organic compounds	-11.7	-6.5	-6.8
Sulphur oxides	-4.6	-6.8	-6.4
Carbon dioxide	-12.5	-12.5	-12.3

Notes:

[a] The Bergen target implies a 14.6% reduction in CO_2 emissions from fossil fuel combustion compared to levels projected for the year 2000.

[b] Coal, natural gas, motive fuels (an aggregate of motor gasoline, diesel fuel oil, aviation gasoline and aviation turbo fuel) and non-motive fuels (an aggregate of petroleum coke, kerosene, light fuel oil and heavy fuel oil).

[c] $27.70 per tonne of carbon dioxide (1990 dollars).

[d] Applicable to iron and steel, electric utilities, transportation and services -- carbon dioxide emissions are reduced by 19% in each industry; simulation also includes a carbon tax on fossil fuels in final demand.

[e] Hicksian compensating variation.

[f] Ratio of average price of exports to average price of imports.

[g] Percentage of base GDP at factor cost.

[h] Percentage of workers that move from one industry to another.

[i] Tax rate equals $27.70 per tonne of carbon dioxide on fossil fuel use in final demand (1990 dollars) -- equivalent to 7.6¢ per litre of gasoline. Tax revenues generated amount to $2.4 billion.

standards are arbitrarily imposed on four industries (iron and steel, electric utilities, transportation and services), which are the most polluting in terms of carbon dioxide emissions from fuel combustion, while a carbon tax is simultaneously applied to fossil fuel use in final demand at the same rate as in the carbon tax scenario.[18] In addition to taxing fossil fuel use in final demand, reducing carbon dioxide emissions by 19 per cent in each of the four industries results in the desired 15 per cent decrease in the equilibrium flow rate of CO_2 emissions from fossil fuel combustion for the economy as a whole.

In achieving the CO_2-emission target, each of the economic instruments adversely affects aggregate economic performance to differing extents. Real GDP at factor cost falls by between 0.5 per cent under the carbon tax and 0.8 per cent under industry emission standards. Offsetting this deterioration in real GDP, however, are positive impacts on Canada's term of trade (index rises by between 1.0 per cent under the carbon tax and 1.2 per cent under emission standards) and on capital imports (decrease of between 0.2 per cent under the carbon tax and 0.3 per cent under emission standards). As a result, real income in Canada declines by smaller amounts ranging from 0.3 per cent for the carbon tax scenario to 0.5 per cent in the case of the fossil fuel tax.

The relatively superior cost effectiveness of the carbon tax is due to this tax being designed to achieve the objective of controlling carbon dioxide emissions in the most comprehensive and direct manner. The carbon tax applies to all fossil fuels (the source of 85 per cent of carbon dioxide emissions in Canada in 1985) and more carbon-polluting fuels are, *ceteris paribus*, taxed at a higher rate. Simulated ad valorem carbon tax rates in table 2 range from 14 per cent for motive fuels to 140 per cent for coal. Other types of economic instruments are not as cost effective in achieving this environmental objective: the deterioration in real income is higher under both a tax on fossil fuels that is not targeted specifically to their carbon content and emission standards that do not specifically target industrial uses of fossil fuels.

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[18] In aggregate, these four industries accounted for 73 per cent of carbon dioxide emissions from fossil fuel combustion in Canadian industries in 1985. Carbon dioxide emissions from fossil fuel use in final demand comprised 24 per cent of total carbon dioxide emissions from fuel combustion in 1985.

As shown in table 2, the fossil fuel tax, imposed at a uniform rate of 33 per cent on the prices of all fossil fuels, is equivalent, in terms of its impact on the price of gasoline, to a specific price increase of over 17 cents per litre. In recognition of its lower carbon content per unit of energy relative to most other fossil fuels, on the other hand, a carbon tax designed to achieve the Bergen target would imply a smaller 7.6 cents per litre rise in the price of gasoline (about 14 per cent). While being the most cost effective of the tax instruments considered in meeting the emission target, the carbon tax is also the least burdensome in that it raises the smallest amount of government revenue. At a rate of $27.70 per tonne of CO_2, the carbon tax would raise $11.2 billion (1990 dollars) in government revenues. The revenue-generating ability of the fossil fuel tax is higher at $13.4 billion. (Emission standards do not generate revenues for government.[19])

An important message emerges when comparing regulatory emission standards with the market instruments. Accepting that, in some cases, regulations may be preferable because market instruments cannot work, conventional wisdom is that market instruments are preferable to regulatory standards in all cases where the use of market instruments is feasible. This assertion is not borne out in our simulations, however. While our results show that the most cost-effective market instrument (i.e., the carbon tax) in meeting the emission target is indeed superior to regulations (i.e., the emission standards), they also show that some market instruments (i.e., the fossil fuel tax) that are not as well suited to achieving this particular environmental goal can turn out to be inferior to well-conceived regulatory standards. Our arbitrarily-selected emission standards are found to rank ahead of the fossil fuel tax in terms of their effects on real income.[20]

In aggregate, gross output declines under emission-reducing tax instruments and emission standards. However, gross output changes vary significantly among individual industries both in absolute and relative terms. Differing industry impacts resulting from

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[19] The carbon tax on fossil fuels in final demand that is imposed, simultaneously with emission standards in this simulation, raises $2.4 billion in government revenues.

[20] In the limit, if emission standards are chosen to reduce carbon dioxide emissions for each model industry by amounts identical to the reductions achieved in the full carbon tax scenario then these standards would be cost effective within the context of the CGE model and its behavioural assumptions. It should be kept in mind, however, that such a simulation would not include other costs, such as informational, administrative, compliance and monitoring costs, that can be non-negligible, particularly for emission standards.

policies to control carbon dioxide emissions can be explained by the interaction of four factors: the burden imposed by the environmental policy, its direct and indirect impacts on commodity prices, and substitution possibilities available to economic agents. Environmental policies cause prices of commodities directly affected to increase -- the more stringent the policy, the higher the price increase. As prices rise, demand for output of the industries directly affected falls. Environmental policies also indirectly affect the prices of commodities which employ the targeted commodities as factors in their production. This indirect price effect exerts a further negative influence on gross output. Offsetting these adverse effects, however, is the ability of producers and consumers to substitute to commodities that are influenced to a lesser degree by environmental policies.

For each of the tax scenarios, the refinery industry is the most severely affected in terms of the extent to which gross output contracts. The output decline of the transportation industry is second largest under the fossil fuel tax, while the fall in iron and steel industry output ranks second in the case of the carbon tax. The poor performance of the refinery industry relative to other industries affected by the uniform fossil fuel tax arises since refinery products (motive and non-motive fuels) account for the majority of CO_2 emissions from fossil fuel combustion (45 per cent) and are used more extensively among industries than coal -- the most carbon-polluting fossil fuel per unit of energy content.[21] In comparison to the carbon tax scenario, the output decline of the refinery industry is also higher in absolute terms under the fossil fuel tax. This is explained by the differentiation of carbon tax rates among fossil fuels -- compared to the fossil fuel tax, the carbon tax rate applicable to coal in meeting the Bergen target is over four times as high while the rate applicable to refinery products (and natural gas, the least carbon-polluting fossil fuel per unit of energy content) is significantly lower.

In contrast to the situation obtaining in the tax scenarios, the iron and steel industry fares worst from the imposition of emission standards (gross output declines by 10.6 per cent) followed by the electric utilities, refinery and transportation industries. Except for the refinery industry, the gross output of which is basically unchanged in comparison to the carbon tax simulation, each of these industries is directly affected by emission standards.

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[21] 93 per cent of coal use is in the electric utilities (80 per cent) and iron and steel (13 per cent) industries.

Gross output of the service industry, also directly subject to regulation, expands by a smaller amount under emission standards than under each of the tax options.

The relative performance of the regulated iron and steel, and electric utilities industries arises primarily because coal is an important factor of production and possibilities for substituting coal for other fuels in these industries are limited. In the carbon tax scenario, the electric utilities industry, in particular, experiences a smaller decline in gross output (2.6 per cent) due to substitution and output/demand changes taking place in other industries and in the residential sector that are sufficient for meeting the Bergen target. Under an emission standard that is specifically designed to constrain its emissions, however, the electric utilities industry cannot rely on emission-reducing actions of other agents and, given its limited substitution possibilities, must curtail its output in order to meet the target. The fall in gross output of the refinery industry under emission standards primarily reflects their impact in reducing demand for refinery products, particularly motive fuels, in the transportation and service industries. The service industry is a relatively large sector in the model that utilizes many intermediate inputs in small proportions. The increase in the price of service products is, consequently, small relative to other commodities under the three policy options modelled, but is larger relative to other commodities under emission standards than under the taxes considered. The CGE analysis reveals that the ensuing shift in demand towards service products fully offsets the negative influence of their price increase, and output of the service industry expands, but less so under emission standards.

It is very important to note that economic instruments for stabilizing carbon dioxide emissions also impact indirectly on emissions of other air pollutants. The draft March 1990 *Management Plan for Nitrogen Oxides and Volatile Organic Compounds* contains 61 regulatory initiatives to reduce nitrogen oxide and volatile organic compound emissions by 16 per cent and 19 per cent, respectively, below their 1985 levels by 2005. This is equivalent to reductions of 16.3 per cent for nitrogen oxides and 28.8 per cent for volatile organic compounds below their levels otherwise forecast for 2005. It is noteworthy that

these aggregate targets are satisfied, to a significant extent and particularly for nitrogen oxides, by all three economic instruments in the simulations of CO_2 emission reduction.[22]

These results for non-CO_2 emissions highlight another important role that CGE models can play in analyzing environmental policies. In addition to their ability to capture, and quantify, the impact of a policy change on all sectors of an economy, they also reveal the interaction among all pollutants under consideration resulting from the policy change. A CO_2-emission policy that is designed to constrain the use of fossil fuels through taxation in attaining its objective will affect, in a complementary manner, emissions of as many pollutants as are embodied in fossil fuels. Quantitative CO_2-emission restrictions achieve a similar effect on emissions of pollutants -- not only will targeted firms substitute, to the extent possible, among polluting inputs to meet a standard, however, they will also seek to limit emissions that arise in the industrial processes they employ. As indicated in the simulations presented in table 2, in pursuing a particular environmental objective, a single economic policy instrument can, therefore, succeed in significantly, although indirectly, achieving multiple environmental objectives.

(b) Alternative targets met through a carbon tax

Figure 5 presents simulation results from using carbon taxes to achieve increasingly demanding target reductions in carbon dioxide emissions from fossil fuel combustion. In addition to the Bergen target, the Toronto target is frequently referred to in the literature. Proposed at the World Conference on the Changing Atmosphere held in Toronto in June 1988, it calls for a reduction in CO_2 emissions to 80 per cent of their 1988 levels by 2005. Achieving the Toronto target is equivalent to reducing aggregate CO_2 emissions by 38.4 per cent of their levels otherwise forecast for 2005. An alternative target to achieve the same level of reduction as the Toronto target is to limit CO_2 emissions to 72 per cent of their 1988 levels by the year 2000. This latter "Toronto-type target" is specifically singled out, along with the Bergen target, in figure 5.

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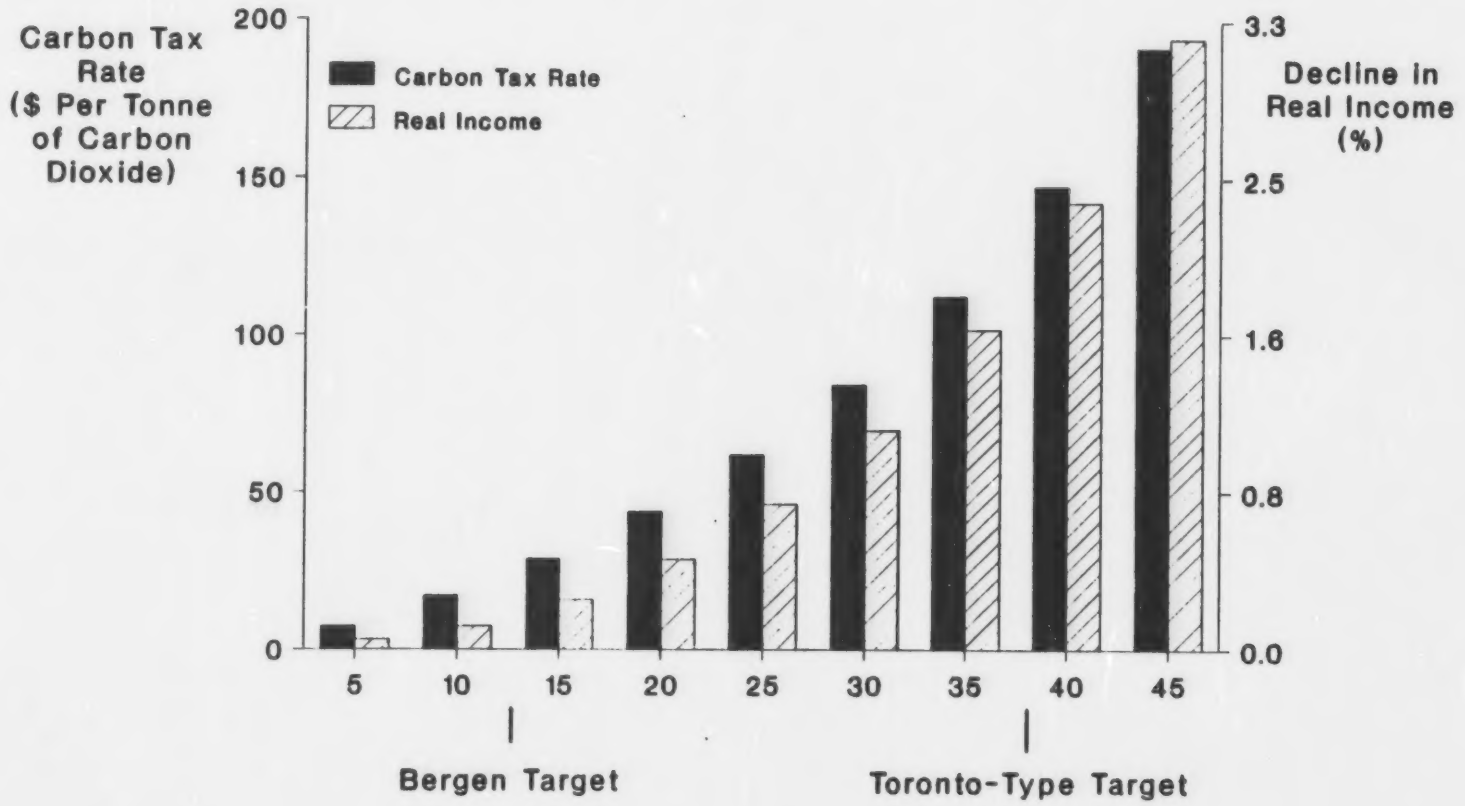
[22] It should be noted, however, that the industrial/residential composition of these aggregate reductions in pollutant emissions is not the same through the economic instruments simulated as would be achieved through the emission standards being proposed in the NOx/VOCs Plan.

Figure 5

Carbon Taxes, Real Income Effects and Emission Targets



The results show that the rate of carbon tax and the associated decline in real income rise, at an increasing rate, as CO_2 emission targets become more stringent. In addition, it is indicated that real income declines at a faster rate than the carbon tax rate increases as the level of environmental protection becomes more demanding. This latter finding is in accordance with economic theory to the effect that the excess burden of a tax is an increasing function of the tax rate.

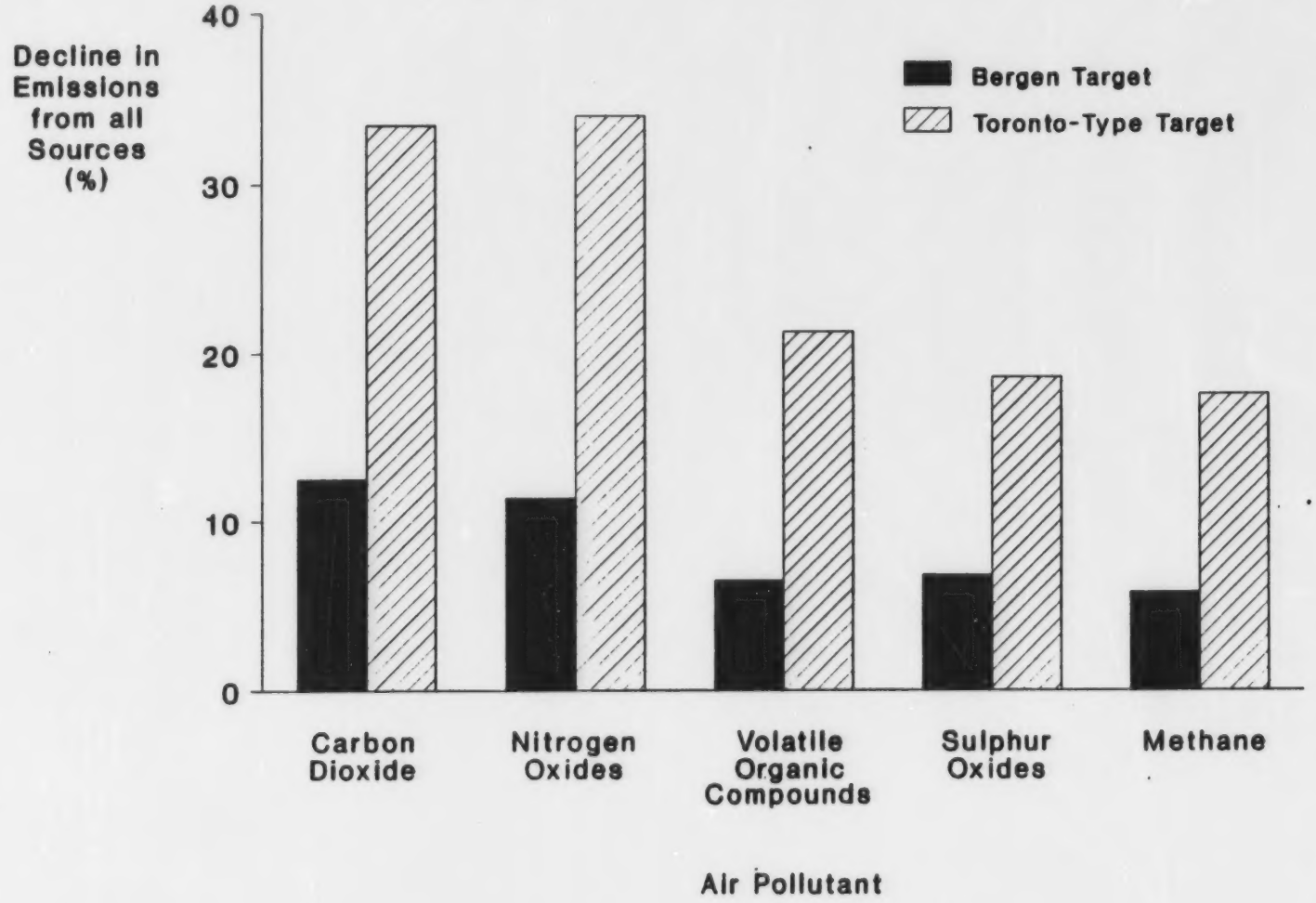
As mentioned previously, the optimal target for environmental change would be that for which the marginal economic cost just equals the marginal benefit of environmental protection. Our analysis provides estimates of only the economic costs of environmental targets. Without adequate information of the schedule of marginal benefits, we are not in a position to judge which of the targets analyzed is preferable.

What we can say, however, based on the analysis presented in figure 5, is that the economic cost of incremental environmental policy actions increases with the size of the emission-reduction target. This increasing marginal cost implies that the net marginal benefits from incremental policy actions will be exhausted at a lower emission-reduction target than if the marginal cost of emission reduction was constant. This underlines the importance of an increasing degree of caution in setting more stringent environmental targets. Our results also stress the need for independent analysis in determining the benefits of a cleaner environment to ascertain the optimal emission-reduction target.

As discussed in the preceding section, in pursuing its objective to reduce emissions of carbon dioxide, a carbon tax exerts an important influence on emissions of other air pollutants as well by changing relative prices and, thereby, altering the economic behaviour of producers and consumers. Since fossil fuels embody pollutants other than carbon dioxide, an emissions policy that constrains the use of fossil fuels will affect each of these pollutants in a complementary manner. As shown in figure 6, the achievement of a more ambitious CO_2 target leads to larger reductions in each of the air pollutants modelled. In the case of the Bergen target, for example, the rate of carbon tax is set at a level that is almost sufficient to reduce emissions of nitrogen oxides in keeping with NOx/VOC Management Plan targets, and that significantly reduces emissions of volatile organic compounds. For the more stringent Toronto-type target, the indirect impact of the carbon

Figure 6

Complementary Environmental Effects of Reducing Carbon Dioxide Emissions



tax on NOx emissions is more than sufficient to satisfy the aggregate Management Plan target. The impact on volatile organic compounds is substantially larger than in the case of the Bergen target to the extent that the aggregate Management Plan target for VOCs is almost attained.

It is also evident in figure 6 that the additional reduction in pollutants from pursuing a more demanding emission target is not necessarily equi-proportional. This is due to differences in uses, prices and pollution contents of individual sources of pollution. The relative impact of a carbon tax in achieving the more stringent Toronto-type target is greater, for example, on nitrogen oxides than on carbon dioxide and on volatile organic compounds than on sulphur oxides.

4.2 Sulphur Oxide Emission Control

Illustrative model results are presented in this section for reducing emissions of sulphur oxides (primarily sulphur dioxide) in accordance with the overall target set out in the federal-provincial Acid Rain Control Program. This agreement between the federal government and the governments of the 7 provinces east of Saskatchewan calls for a reduction in SOx emissions of approximately 45% from 1980 reference-year levels by 1994.[23]

Two simulations are discussed and compared. In the first, quantitative emission constraints are imposed on those industries we have been able to specifically identify under the Acid Rain Control Program. At the same time, an emission charge is imposed on all other industries to achieve an economy-wide reduction in SOx emissions in approximate accordance with the overall federal-provincial SOx target. In the second simulation, an emission charge is imposed on all industries to meet the federal-provincial target.

It should be noted that imposing an emission constraint or an emission charge on SOx emissions has different effects on industries which produce Armington versus homogeneous commodities. This differential effect arises due both to the price-setting

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[23] A breakdown of SOx-reduction requirements by firm within each province is provided in table B7.

versus price-taking behaviour of these industries and to the presence of a fixed factor of production in some Armington- and all homogeneous-goods producing industries.[24]

For the case of Armington industries which do not depend on a fixed primary factor of production, the pollution policy results in an increase in the implicit cost of the polluting input which is proportional to the SOx content per unit of the input. In general, any increase in the cost of these inputs generates an increase in the marginal production cost and consequently, an increase in the price of industry output. In the case of homogeneous commodities, however, the output price is set at the world price for the good (plus tariffs). As a result, the increased production costs resulting from imposing an emission constraint or charge are entirely absorbed through a reduction in the rent accruing to the fixed factor of production, namely, the sector-specific resource factor. For those Armington industries in which a fixed factor of production is present, a portion of the increased cost of production reduces the rent to the sector-specific factor while the remaining portion is reflected in a higher output price -- the burden of the tax is shared by both the rent-owner and the consumer.

(a) Quantitative constraints and an emission charge

Given the accomplishments realized to date under the Acid Rain Control Program and allowing for continued growth in emissions over the remaining period to 1994, we model the following industry-specific standards to meet commitments under the agreement: a 20% reduction in SOx emissions in the iron and steel sector; a 48% reduction in the non-ferrous smelting sector; and a 48% reduction in the electric utilities sector. The standards are imposed on emissions from the use of coal, natural gas and non-motive fuels, and from industrial processes. In addition to these quantitative emission constraints, we impose an aggregate SOx emission limit on the remaining industrial sectors of the model by means of an emission charge, imposed on SOx emissions from stationary fuel combustion in industry and on industrial processes, which achieves a 40 per cent reduction for the economy as a whole.

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[24] Table B14 provides a summary of which industries produce Armington versus homogeneous goods and which industries require a fixed factor in production.

The results of this "partial Acid Rain Control Program" simulation are presented in table 3. The emission charge equals $1254 per tonne of SOx. Real GDP at factor cost declines by 0.2 per cent as a result of imposing industry-specific standards together with an emission charge. However, due to the positive impact on the terms of trade (increase of 0.3 per cent), and the fact that net capital imports decrease by 0.1 per cent, the loss in real GDP is partly offset, and real income decreases by a smaller 0.13 per cent as a result.

Constraining the quantity of SOx emissions results in higher production costs for the industries affected. As noted above in section 3.2(a), when the emission constraint is binding, there is a positive shadow price associated with each unit of pollutant emitted. Several options are available to industries for minimizing the effects of this additional cost. One concerns substitution possibilities: substituting less-polluting fossil fuels for more-polluting fossil fuels, substituting electricity for fossil fuels, or substituting other inputs for energy. Industry outputs can also be reduced. In addition, industries can invest in various technologies to enable them to reduce pollution levels while continuing to employ the same quantity of inputs. As long as the marginal cost of investment in pollution control technologies is less than the shadow cost associated with the constraint, the latter option will be the one chosen by industry since it is the least costly.

The sectoral impact of this pollution policy depends on how well the industries adapt to the new market conditions and on the effectiveness and the cost of the abatement technology that is available to them. The simulation results show that all industries that have access to abatement technologies, purchase abatement capital; only the three regulated industries do not purchase the full amount available to them since the SOx reduction through abatement capital necessary to meet their specific emission constraints is less than the maximum percentage reduction available. End-of-stack SOx abatement technologies are available to nine industries in the model: non-ferrous smelting, light manufacturing, pulp and paper, iron and steel, refineries, chemicals, other manufacturing, electric utilities and services.[25] The total cost of capital abatement purchases by these industries is $707.5 million.

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[25] See appendix B.3 for detail on the types and costs of abatement capital available to these industries.

Table 3
Acid Deposition Reduction
(per cent change except as noted)

	Partial Acid Rain Control Program	Uniform Industry-Wide Emission Charge
Real Income[a]	-0.13	-0.11
Real GDP at Factor Cost	-0.2	-0.3
Terms of Trade Index[b]	0.3	0.4
Net Capital Imports[c]	-0.1	-0.1
Labour Reallocation Index[d]	0.2	0.2
Change in Gross Output:		
Non-ferrous smelting	-4.2	-14.9
Iron & steel	-3.6	-2.9
Electric utilities	-1.7	-1.8
Pulp & paper	-1.6	-0.9
Refineries	-1.3	-0.9
Coal	-0.7	-0.5
Crude oil & natural gas	0.1	-1.2
Average - all industries	-0.3	-0.4
Purchases of Abatement Capital (1990 $ millions)	707.5	349.8
Emission Charge (1990 $) $ per tonne of sulphur oxides	1254.3	833.0
Emission Charge Revenues (1990 $ billions)	3.0	2.0
Total Emissions, Canada:		
Nitrogen oxides	-1.7	-1.5
Methane	-1.1	-0.8
Volatile organic compounds	-0.5	-0.4
Sulphur oxides	-40.1	-40.4
Carbon dioxide	-2.3	-2.1

Notes:
[a] Hicksian compensating variation.
[b] Ratio of average price of exports to average price of imports.
[c] Percentage of base GDP at factor cost.
[d] Percentage of workers that move among industries.

As shown in table 3, the non-ferrous smelting industry is most affected (gross output declines by 4.2 per cent) followed by the iron and steel industry and the electric utilities industry. The implications of this option become evident in comparing the results of this simulation with the simulation described in the following section.

In considering complementary environmental impacts of the policy, it is evident that the policy option modelled to control sulphur oxide emissions has very limited effects on other air pollutants. This result stands in marked contrast to the carbon tax analyzed in the preceding two sections, and is due to the fact that the majority of sulphur dioxide emissions (65 per cent) arise from industrial sources rather than fossil fuel combustion.

(b) Uniform industry-wide emission charge

In this simulation, a uniform industry-wide emission charge is imposed on SOx emissions. The charge is determined in such a way that the overall reduction in SOx emissions is 40 per cent -- the same target analyzed in the preceding section. The model results, presented in table 3, indicate that the level of the charge must be $833 per tonne of SOx in order to obtain this target.

One of the key points to note is that the loss in real income under the emission charge (-0.11 per cent) is less than the real income loss arising from the joint emission constraint/charge analyzed previously. Thus, SOx reduction under an emission charge occurs in a more cost-effective manner than a combination of industry-specific standards and emission charges. This is explained by the fact that, under a charge, the market will determine which industries are the most efficient in reducing emissions. Those industries best able to substitute among factors of production, reduce output or invest in abatement technologies will do so to reduce emissions rather than pay the tax. Industries in which the cost of the charge is less than the cost of other available options for emission reduction will pay the tax rather than lower their emission levels.

At the sectoral level, it is interesting to note that the decrease in gross output in the non-ferrous smelting industry is over 3 times higher (14.9 per cent) under an emission charge than under the joint emission constraint/charge scenario (4.2 per cent). This large reduction in gross output under an emission charge is due to two factors.

First, the cost of abatement technologies for other industries is generally higher than the emission charge. Hence, at the margin, these other industries prefer to pay the charge and pollute, rather than to purchase abatement capital and thereby reduce their own emissions of sulphur oxides. This means that the bulk of SOx emission reduction is left to industries (specifically, the non-ferrous smelting industry and the electric utilities industry) that can acquire relatively less expensive abatement capital. In fact, the non-ferrous smelting industry purchases the full amount of abatement capital available to it under the emission charge in contrast to its behaviour under an emission standard.

Second, even though the non-ferrous smelting industry acquires all the abatement capital available to it, the overall emission target would still not be met solely in this manner -- SOx emission reduction through abatement capital is limited. In order that SOx emissions are further reduced, the level of the emission charge ($833 per tonne of SOx) must be substantially higher than the cost of acquiring abatement capital for the non-ferrous smelting industry ($85 per tonne of SOx). It is the case both that the non-ferrous smelting industry has the highest SOx-emission-per-unit-of-output ratio and that these emissions arise almost exclusively from the industrial process employed rather than from the combustion of fossil fuels. These two factors imply that the non-ferrous smelting industry is the most severely affected industrial sector under an emission charge and, given the impossibility of substituting, to any significant degree, among less polluting inputs, the unfavourable output effect of the charge is pronounced. This contrasts with the results of the previous simulation in which the non-ferrous smelting industry (as well as the iron and steel, and electric utilities industries) is able to meet its specified reduction in SOx emissions entirely through investment in abatement technologies; in combination with these regulated industries, the emission-reducing activities of other economic agents then allows the overall SOx target to be met.

5. Concluding Remarks

The environmental CGE model presented here is one of few computational models currently available which describes in detail the relation between economic activity in Canada and the United States and the resulting flow rates of emission of five common air pollutants of current concern. It is, moreover, one of very few simulation models in which agents' responses to pollution-control policies (particularly changes in factor and commodity demands, output supplies, and demands for pollution-abatement technologies) are the result of endogenous, optimizing behaviour rather than ad hoc adjustments imposed by the modellers themselves. Some general ways in which our environment model can be put to advantage in environmental policy analysis are outlined in the box on the next page.

As used in this paper, the environment model provides indications of the nature and the degree of resource reallocations and real income change, over the longer term, that are necessary to meet exogenously-specified reductions in pollutant emissions through the use of various economic instruments, including relatively unconventional anti-pollution policies such as emission standards, emission charges and tradable permit systems. While scientific and economic uncertainties remain over the economic benefits of environmental protection and, consequently, the extent to which action should be taken, it is nonetheless generally agreed that, if the North American economies are to meet emission targets now being considered by policy-makers and scientists, reallocation effects are apt to be significant. In particular, agents will have to be induced to make less intensive use of polluting inputs in production and consumption, to limit production of inherently polluting outputs and to invest in emission-control technologies. As the model provides a disaggregated description of the major energy sources and polluting activities, it is able to describe such responses in considerable detail. With such wholesale changes in economic activity, one can expect significant changes in factor prices, international terms of trade and, hence, consumer welfare. It follows naturally that one would seek to determine how to minimize disruption to the economy while pursuing environmental objectives. The environment model can assess and rank alternative environmental policy options in terms of their cost effectiveness and environmental consequences.

A Useful Tool for Environmental Policy Analysis

The basic purpose of the environment model is to investigate and better understand, in a longer-term perspective, how national economies and policies affect the environment, and how the pursuit of environmental objectives affects national economies. Currently, the model can indicate how emissions of air pollutants would change as a result of changes in economic activity in Canada and the United States. Obversely, the model can analyze how economic activity -- and, consequently, consumer welfare -- in North America must change in order to meet particular environmental policy goals. As an analytic tool, our CGE environment-economy model can provide guidance by:

- assessing and quantifying the economic costs (both economy-wide and sectoral) of achieving either a given environmental target using alternative economic instruments or a range of environmental targets using a single economic instrument -- this information allows instruments to be ranked in terms of their cost effectiveness and helps assess the desirability of environmental objectives in terms of their economic implications;

- investigating the complementary impacts of an economic instrument for controlling a single pollutant on flows of other pollutants -- interrelationships that need to be taken into consideration when setting policy objectives;

- calculating rates of tax and emission charges, and their revenue impacts, for meeting a given environmental objective;

- providing an assessment of certain bilateral environmental issues through explicit modelling of the U.S. economy -- this is important since U.S. environmental policies impact on Canada, and vice versa (Our ability to model U.S. environmental policy initiatives is limited at present due to a lack of sufficiently disaggregated emissions data for the United States.); and

- allowing a limited analysis of multilateral initiatives. (Although the model is not world-wide in scope, ad hoc assumptions can be made about changes in world prices that result from international environmental initiatives.)

Before proceeding to summarize the main conclusions stemming from the model simulations, it may be useful to stress, once again, certain of the model's limitations and underlying assumptions so as to allow the findings to be viewed, hopefully, in a proper perspective. Since they are not available, economic benefits of environmental protection are not included in the model -- this precludes analyzing issues of sustainable

development and the "efficiency" (but not the cost effectiveness) of economic instruments. The environment model, like all CGE models, takes a longer-term perspective -- it is not able to comment on shorter-term or transitional issues which may not be insignificant. Altering the model's underlying assumptions, an example being zero administration, compliance and monitoring costs, and key substitution elasticity parameters, may alter the model's results. Finally, model results reflect the focus of the analysis which is on achieving environmental policy goals -- the model's findings may change if alternative policy objectives are simultaneously pursued.

Our use of the environment CGE model to investigate alternative policy options for reducing emissions of carbon dioxide and sulphur oxides in Canada has allowed us to gain insights into their economic and environmental impacts. The results of the model simulations undertaken both reinforce some basic economic principles, and highlight economic and environmental issues in need of attention and further consideration.

- To be cost effective, environmental policies need to target the source(s) of the problem. For example, if the objective is to reduce the concentration of carbon in the atmosphere, policy should deal directly and comprehensively with reducing emissions of carbon dioxide. As the results of the CO_2-reduction simulations show, the most cost-effective instrument for achieving this objective is a carbon tax since it is the most comprehensive of the economic instruments considered and it is designed to achieve its objective in the most direct manner.

- This environmental policy conclusion is also in accordance with conventional wisdom that the use of appropriate market instruments, where feasible, is preferable to the use of regulatory standards. Conventional wisdom in this regard is upheld as well in the SOx simulations. It should be noted, however, that quantitative emission standards can be more cost effective in achieving environmental objectives than poorly-designed market instruments. Illustrative standards in our model, applicable to the four most-carbon-polluting industries, are found to be more cost effective in terms of their impact on real income than is a fossil fuel tax in reducing emissions of carbon dioxide.

- As concerns the relative ranking of market and non-market instruments, therefore, these results help to convey the very important message that there are two considerations that determine which instrument is most effective in minimizing the cost of achieving an environmental objective. The first is the extent to which a policy uses the market to achieve a particular objective -- the greater the reliance on the market, the more cost effective is the instrument. The second consideration is whether an instrument tries to achieve the sought-after objective directly or indirectly. An instrument that uses the market to directly achieve an environmental objective is indeed the most effective. However, when there is a trade-off -- when an instrument uses the market, but goes about achieving the environmental objective indirectly (e.g., a tax on the price of fossil fuels instead of their carbon content), or when an environmental objective is achieved directly, but without the assistance of the market (e.g., emission standards) -- the ranking of policy options becomes less certain. Thus, contrary to conventional wisdom, not all market instruments are necessarily more cost effective than emission standards in meeting particular environmental targets.

- The carbon tax simulations indicate that the rate of carbon tax and associated decline in real income are increasing functions of the carbon dioxide emission target. In order to achieve an emission target that is, for example, twice as stringent, the carbon tax rate needs to be more than twice as high. This finding, which applies to other economic instruments as well, suggests caution in setting targets for pollution control.

- It is said that regulation provides little or no incentive for firms to reduce pollution by more than the required emission standard. Market instruments, on the other hand, are seen as providing a continuous and dynamic incentive for firms to implement new technologies and processes to control pollution if their cost is less than the cost implied by the economic instruments. This point is confirmed by simulation results for controlling emissions of sulphur dioxides in the environment model. The results show that industries subject to emission standards do not purchase the full amount of abatement capital available to them. Under an emission charge which achieves an identical target, however, previously-

regulated industries facing abatement costs lower than the emission charge do purchase all available abatement capital.

- The results of the sulphur oxide reduction simulations also illustrate the importance of capital abatement technologies in reducing pollutant emissions. The availability of abatement technologies can dramatically alleviate adverse substitution and output effects that would otherwise occur in industries for which these technologies are economically feasible alternatives. This is particularly evident for the non-ferrous smelting industry in the model simulations. This finding provides a good example of the importance of CGE models in capturing, and quantifying, the impact of a policy change on all sectors of an economy -- an outcome which would not be forthcoming, by definition, in a partial-equilibrium analysis.

- By revealing the interaction of a single environmental policy on all air pollutants modelled, the simulations also indicate the necessity of accounting for interdependence among a range of pollutants in designing a cost-effective package of economic instruments to achieve a number of environmental objectives. In pursuing a particular environmental policy objective, it is shown that an economic policy instrument can succeed in significantly, although indirectly, achieving multiple environmental objectives. This is particularly striking in the case of controlling emissions of carbon dioxide in which alternative economic instruments designed to achieve a given reduction in CO_2 emissions also have substantial complementary impacts on other pollutants and, therefore, environmental objectives -- it is most notable that aggregate NOx/VOCs Management Plan targets for nitrogen oxides and volatile organic compounds are largely or fully met. Moreover, it is shown that, the more demanding the emission target, the larger are the complementary effects on other pollutants. In achieving more stringent emission targets, however, the additional reduction in pollutants is demonstrated not to be equi-proportional due to differences in uses, prices and pollution contents of individual sources of pollution. Finally, in comparing simulations for controlling carbon dioxide and sulphur oxide, it is shown that the complementary impacts on pollutants can be very different for different environmental policies.

Thus, as demonstrated through the simulations of the environment model, CGE analyses permit us to achieve a better understanding of the qualitative and quantitative interrelationships between various economic and environmental objectives. A good understanding of the issues involved is, in turn, crucial in choosing an appropriate set of policies to address environmental concerns. If environmental policies are well integrated and cost effective, the minimum amount of scarce resources will have to be reallocated to pollution control from other economic pursuits to the ultimate benefit of society as a whole.

Appendix A

Algebraic Description of the Model

Table A1

Algebraic Notation

Symbol		Definition
1. Production		
Y_i	$i \in I$	gross output of industry i
$X_i^{k,m}$	$i \in I$ $k \in G_m$ $m \in M$	intermediate-materials aggregate k in nesting level m of industry i
$V_i^{d,n}$	$i \in I$ $d \in F_n$ $n \in N$	value-added aggregate d in nesting level n of industry i
α_{xi}	$i \in I$	intermediate-materials requirement per unit of output i
α_{vi}	$i \in I$	value-added requirement per unit of output i
X_{ji}	$i \in I$ $j \in C$	demand for commodity j in industry i
V_{ji}	$i \in I$ $j \in P$	demand for primary factor j in industry i
$\bar{V}_j$	$j \in P$	total supply of primary factor j
$a_{ji}(\mathbf{p})$	$i \in I$ $j \in C$	optimal intermediate demand for commodity j per unit of output i
$b_{ji}(\omega)$	$i \in I$ $j \in P$	optimal demand for primary factor j per unit of output i
$\gamma_i^{j,m}$	$i \in I$ $j \in G_{m+1}$ $m \in M$	share parameter for intermediate input j in nesting level m of industry i
$\delta_i^{j,n}$	$i \in I$ $j \in F_{n+1}$ $n \in N$	share parameter for primary input j in nesting level n of industry i
$\sigma_i^{k,m}$	$i \in I$ $k \in G_m$ $m \in M$	elasticity of substitution for intermediate-materials aggregate k in nesting level m of industry i
$\eta_i^{j,m+1}$	$i \in I$ $j \in G_{m+1}$ $m \in M$	compensated own-price elasticity of demand for intermediate input j in nesting level m+1 of industry i
$HI_i^{j,m}$	$i \in I$ $j \in G_{m+1}$ $m \in M$	cost share of commodity or materials aggregate j in nesting level m of industry i

Table A1 - Continued

Symbol		Definition
$\rho_i^{d,n}$	$i \in I$ $d \in F_n$ $n \in N$	elasticity of substitution for value-added aggregate d in nesting level n of industry i
$\eta_i^{j,n+1}$	$i \in I$ $j \in F_{n+1}$ $n \in N$	compensated own-price elasticity of demand for primary input j in nesting level n+1 of industry i
$HV_i^{j,m}$	$i \in I$ $j \in F_{m+1}$ $n \in N$	cost share of primary factor or value-added aggregate j in nesting level m of industry i
$HV_i^{n,y}$	$i \in I$ $n = 2$	cost share of value added in revenue of resource or electric utilities industry i
$HV_i^{n+1,y}$	$i \in I$ $n = 2$	cost share of fixed factor in revenue of resource or electric utilities industry i
C_i	$i \in I$	cost function for industry i
$c_i(\mathbf{q},\mathbf{w})$	$i \in I$	cost function per unit of output i
$c_i^{k,m}$	$i \in I$ $k \in G_m$ $m \in M$	cost function for intermediate-materials aggregate k in nesting level m of industry i
$c_i^{d,n}$	$i \in I$ $d \in F_n$ $n \in N$	cost function for value-added aggregate d in nesting level n of industry i

2. Final Demand

U^l	$l \in L^*$	utility function for consumer in region l
$Z^{k,s}$	$k \in C_s$ $s \in S$	final demand for commodity aggregate k in nesting level s
Z_j	$j \in C$	final demand for commodity j
$\beta^{j,s}$	$j \in C_{s+1}$ $s \in S$	share parameter for commodity or commodity aggregate j in nesting level s
$\varepsilon^{k,s}$	$k \in C_s$ $s \in S$	elasticity of substitution for good k in nesting level s in preferences
$\eta^{j,s+1}$	$j \in C_{s+1}$ $s \in S$	uncompensated own-price elasticity of demand for commodity or commodity aggregate j in nesting level s+1
$HC^{j,s}$	$j \in C_{s+1}$ $s \in S$	expenditure share of commodity or commodity aggregate j in nesting level s

Table A1 - Continued

Symbol		Definition
3. Prices and Taxes		
p_i	$i \in I$	producer (or border) price of good i
$\bar{p}_i^w$	$i \in I$	fixed world price (excluding tariff) of homogeneous good i
$P^{k,s}$	$k \in C_s$ $s \in S$	market price of commodity aggregate k in nesting level s
ω_j	$j \in P$	net-of-tax return to primary factor j
$q_i^{k,m}$	$i \in I$ $k \in G_m$ $m \in M$	market price of intermediate-materials aggregate k in nesting level m
$w_i^{d,n}$	$i \in I$ $d \in F_n$ $n \in N$	market price of value-added aggregate d in nesting level n
q_{ji}	$i \in I$ $j \in C$	market price of commodity j in industry i
w_{ji}	$i \in I$ $j \in P$	market price of primary factor j in industry i
t_{ji}	$i \in I$ $j \in C$	tax on the use of intermediate factor j in industry i (includes tariff)
τ_{ji}	$i \in I$ $j \in P$	tax on the use of primary factor j in industry i
t_i^p	$i \in I$	tax on the output of industry i
R^l	$l \in L^n$	government revenue in region l
4. Foreign Sector		
T_i^l	$i \in C$ $l \in L$	imports of commodity i by region l
$KM^{k,l}$	$k \in L$ $l \in L$	imports of capital services from region k to region l
5. Pollution		
E_i^k	$i \in I$ $k \in K$	emissions of pollutant k in industry i
e_{ji}^k	$i \in I$ $j \in C$ $k \in K$	marginal emissions of pollutant k from the use of commodity j in industry i (constant)
$e_i^{k,y}$	$i \in I$ $k \in K$	marginal emissions of pollutant k from production in industry i (constant)

Table A1 - Continued

Symbol		Definition
A_i^k	$i \in I$, $k \in K$	demand for abatement capital for pollutant k by industry i
$e_i^{k,A}$	$i \in I$, $k \in K$	marginal reduction in emissions of pollutant k from purchase of abatement capital by industry i (constant; negative)
$r^{k,A}$	$k \in K$	unit cost of abatement capital for reducing emissions of pollutant k
$\bar{E}_i^k$	$i \in I$, $k \in K$	maximum permissible emissions of pollutant k in industry i
$\bar{R}_i^k$	$i \in I$, $k \in K$	maximum feasible percentage reduction in emissions of pollutant k from purchase of abatement capital in industry i
λ_i^k	$i \in I$, $k \in K$	marginal cost of achieving emission target $\bar{E}_i^k$ for pollutant k by industry i
Λ_i^k	$i \in I$, $k \in K$	marginal cost of emissions of pollutant k in industry i
μ_i^k	$i \in I$, $k \in K$	marginal cost of achieving emissions reduction $\bar{R}_i^k$ for pollutant k by industry i
π^k	$k \in K$	market price of emission permits for pollutant k
θ^k	$k \in K$	emission charge on pollutant k
6. Index Sets		
I^l	$l \in L$	set of industries in region l
C^l	$l \in L$	set of commodities in region l
M		set of nesting levels in production for intermediate-materials aggregate (2,...,5)
N		set of nesting levels in production for value-added aggregate (2,3 for resource industries; 2 for other industries)
S		set of nesting levels in consumption (1,...,5)
P		set of primary factors in region l
G_m	$m \in M$	set of commodities or aggregates of commodities at nesting level m
F_n	$n \in N$	set of primary factors or aggregates of primary factors at nesting level n
C_s	$s \in S$	set of commodities or aggregates of commodities at nesting level s
L^n		set of endogenous regions (2)
L		set of endogenous and exogenous regions (3)
K		set of pollutants

Table A2

Income Identities and Equilibrium Conditions

A. Identities

1. Income Definition

$$(I.1) \qquad GNP^{l} = \sum_{i \in F} \sum_{k \in L^{*}} \Phi_{i}^{l,k} \bar{F}_{i}^{k} w_{i}^{k} + R^{l} + \bar{K}^{l} \qquad l \in L^{*}$$

where $\Phi_{i}^{l,k}$ is the share of the initial stock of factor i in region k that is owned by region l, and $\bar{K}^{l}$ are exogenous capital-income transfers from the ROW to the endogenous regions.

2. Final Demand Expenditures

$$(I.2) \qquad GNE^{l} = \sum_{i \in C} p_{i} \, (1 + t_{i}^{l,fd}) \, Z_{i}^{l} \qquad l \in L^{*}$$

where $t_{i}^{l,fd}$ is a final demand tax on commodity i in region l.

3. Government Revenues

$$(I.3) \qquad R^{l} = \sum_{i \in C} p_{i} \, t_{i}^{l,fd} \, Z_{i}^{l} + \sum_{j \in I^{l}} [t_{j}^{p} / (1 + t_{j}^{p})] \, p_{j} \, Y_{j}$$

$$+ \sum_{j \in I^{l}} \sum_{i \in C} t_{ji} \, p_{i} \, X_{ji} + \sum_{j \in I^{l}} \sum_{f \in F} \tau_{fj} \, w_{f} \, V_{fj} + \sum_{k \in P} \theta_{lk} \, E_{lk}, \qquad l \in L^{*}$$

4. Income-Expenditure Identity (Say's Law)

$$GNP^{l} = GNE^{l} \qquad l \in L^{*}$$

(This is implied by equations I.1 to I.3.)

Table A2 - Continued

B. Equilibrium Conditions

1. Material Balances

a) commodities:

$$(E.1) \qquad \sum_{j \in I} X_{ji} + \sum_{l \in L^*} Z_i^l + T_i^{ROW} - Y_i = 0 \qquad i \in C,\ l \in L^*$$

b) labour (V_{Li}):

$$(E.2) \qquad \sum_{i \in I^*} b_{Li}\, Y_i - \bar{V}_L = 0 \qquad l \in L^*$$

c) capital (V_{Ki}):

- if internationally mobile,

$$(E.3a) \qquad w_K = \bar{w}_K \qquad l \in L^*$$

- if internationally immobile,

$$(E.3b) \qquad \sum_{i \in I^*} b_{Ki}\, Y_i - \bar{V}_K = 0 \qquad l \in L^*$$

d) sector-specific resource (V_{Ri}):

$$(E.4) \qquad b_{Ri}\, Y_i - \bar{V}_R = 0 \qquad i \in I$$

Table A2 - Continued

B. Equilibrium Conditions (continued)

2. Zero-profit conditions

$$(E.5a) \qquad p_i = \left[\sum_{j \in C} a_{ji}(\mathbf{p})\, p_j\, (1 + t_{ji}) + \sum_{k \in P} b_{ki}(\omega)\, \omega_k\, (1 + \tau_{ki}) \right] (1 + t_i^p) \qquad i \in I$$

If the industry produces a homogeneous product, we have additionally

$$(E.5b) \qquad p_i = \bar{p}_i^w$$

and (E.5a) is inverted to solve for the return to the fixed factor as a residual function of the other variables.

3. Current account balance

$$(E.6) \qquad \sum_{i \in C^r} p_i\, T_i^l - \sum_{i \in C^l} p_i\, T_i^k = (KM^{k,l} - KM^{l,k}) \qquad l,k \in L$$

(Although it is omitted from the equation for simplicity, equation (E.6) also takes into account the exogenous capital-income transfers from the ROW to the endogenous regions, i.e., $\bar{K}^l$.)

Appendix B

Data and Parameters

B.1 Input-Output and International Trade Data

1. Canada

Basic input-output data for Canada are based on unpublished "squared" data[26] for 1985 at the "L-level" of industry aggregation[27] obtained from the Input Output Division of Statistics Canada. International trade data for 1985 are also unpublished; they were obtained through the World Trade Database at the L-level of industry aggregation from the International Trade Division of Statistics Canada.

In addition, relative fossil-fuel prices and energy intensities forecast for the year 2000 were obtained from the Inter-Fuel Substitution and Demand (IFSD) Model of energy markets in Canada developed by the Department of Energy, Mines and Resources (EMR) Canada. A counterfactual model simulation, which became the benchmark for subsequent analyses of environmental policies, was then performed to modify the input-output and international trade data to reflect the IFSD forecast.

2. United States

U.S. input-output data for 1984 (the most recent year available) were obtained in unpublished form from the Interindustry Economics Division, Bureau of Economic Analysis of the U.S. Department of Commerce. In order to render them consistent with Canadian figures, the data are inflated by the rise in U.S. nominal gross domestic product in 1985, and converted to Canadian dollars.

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[26] That is, input-output data is converted from commodity-industry space to industry space under an assumption that each industry produces a single, composite commodity. This is accomplished by multiplying the "use matrix" (161 industries and 602 commodities) by the "make matrix" (602 commodities and 161 industries). The proportion of each individual commodity in an industry's total output is assumed to remain fixed at base period levels.

[27] 161 industries and 136 final demand categories.

B.2 Air Pollution Emission Data

1. Canada

Data on emissions of nitrogen oxides, methane, volatile organic compounds, sulphur oxides and carbon dioxide are of three basic types in the environment model: (i) emissions from fossil fuel combustion; (ii) emissions from certain industrial processes; and (iii) exogenous emissions. Canadian data for 1985 for each of these categories are provided in tables B1 to B5.

Fuel combustion emissions in the model were generated using unpublished information contained in Statistics Canada's energy disposition data base[28] and emission factor estimates obtained from the Department of Environment Canada and EMR. The energy disposition data base contains the most detailed information on energy use in Canada -- statistics are available on the use of coal and coke, crude oil, natural gas, liquified petroleum gases, fuel oil, motor gasoline and aviation gasoline in 161 industrial sectors (corresponding to the L-level of industry aggregation), and by households and governments. The most recent year for which these detailed energy-use data are available is 1984. Once aggregated to the industry/final demand categories of the environment model, energy-demand data contained in Statistics Canada (1985) were used to update the numbers to reflect 1985 totals, to disaggregate fuel oil into kerosene, light and heavy fuel oils, diesel fuel oil and aviation turbo fuel, and to include information on petroleum coke. For each of the five pollutants, emission factors by fuel type and industry/sector were then applied to the so-modified energy-demand data to obtain estimates of emissions from fossil fuel combustion, and the emission data set was aggregated to the fossil fuel categories employed in the environment model[29].

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[28] See Statistics Canada (1984) and Hamilton (1988).

[29] Coal and coke, natural gas, motive fuels (motor gasoline, diesel fuel oil, aviation gasoline and aviation turbo fuel) and non-motive fuels (petroleum coke, kerosene, light fuel oil and heavy fuel oil).

Data on industrial process emissions were obtained from Environment Canada (1989) and (1990a).[30] Exogenous emissions in the environment model consist of emissions from residential fuelwood combustion, private electric plants, waste incineration, tire wear, structural fires, dry cleaning, surface coatings and general solvent use.

A comparison is provided in table B6 of Canadian emissions data for 1985 used in the environment model and 1985 data reported in Environment Canada (1989) and (1990a)[31]. Differences between the two data sets in terms of total emissions of air pollutants are small (less than 3 per cent in absolute value) in all cases -- in general, the discrepancy is entirely attributable to emissions from fossil fuel combustion. It should be noted that the procedure for generating fuel combustion emissions in the environment model is employed in an identical manner for each of the 5 air pollutants considered.

2. United States

Aggregate U.S. emissions data for nitrogen oxides, volatile organic compounds and sulphur oxides from industrial processes, stationary fuel combustion sources and transportation, by industry and final demand category, are published by the U.S. Environmental Protection Agency (EPA).[32] Unpublished carbon dioxide emission data, by industry aggregate and by fuel type for mobile and stationary fuel combustion, are also obtained from the U.S. EPA; data on emissions of carbon dioxide from industrial processes are not currently available.

Transformations to U.S. emission data were necessary to make them consistent with the industry aggregation employed in the environment model. U.S. Standard Industrial Classification (SIC) codes were used to aggregate emissions from industrial processes to environment model industries. For emissions from stationary fuel combustion, disaggregation of the "industrial" category to environment model industries was based on

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[30] This published data on industrial process emissions was also supplemented by unpublished data, obtained from DOE, on wood combustion in sawmills in British Columbia.

[31] Data on emissions from fuel combustion and from industrial processes is reported in these publications only by industry/sector and not by individual fuel type.

[32] U.S. EPA (March 1989).

information on fuel use by U.S. industries obtained from the International Energy Agency (IEA).[33] Emission factors by fuel type, identical to those used in generating the Canadian emissions data, are then applied to the fuel-use data for the United States. However, the IEA data do not provide the disaggregate breakdown necessary for the environment model. The data for emissions from fuel combustion are, therefore, not entirely satisfactory and have yet to be fully incorporated into the model.

[33] International Energy Agency (1988).

Table B1

Canadian Nitrogen Oxide Emissions in 1985
(tonnes)

Model category	Emissions from Fuel Combustion					Industrial Process Emissions	Total
	Coal & Coke	Natural Gas	Motive Fuels[a]	Non-Motive Fuels[b]	Subtotal		
1 Agriculture	470.2	1,005.3	75,283.0	896.4	77,655.0	0.0	77,655.0
2 Fishing	0.0	29.2	11,620.9	115.9	11,766.0	0.0	11,766.0
3 Forestry	0.0	35.3	14,496.5	596.3	15,128.1	16,819.0	31,947.1
4 Non-coal mining	806.8	2,574.9	42,156.7	3,679.7	49,218.1	0.0	49,218.1
5 Coal mining	287.9	391.2	8,494.4	0.0	9,173.5	0.0	9,173.5
6 Crude oil & natural gas	0.0	1,227.9	56,675.2	0.0	57,903.2	15,975.0	73,878.2
7 Light manufacturing	46.4	6,799.3	22,413.2	1,841.9	31,100.8	0.0	31,100.8
8 Pulp & paper	2,360.2	6,138.4	31,770.0	11,171.6	51,440.2	47,012.0	98,452.2
9 Iron & steel	44,841.3	3,690.9	1,230.5	1,439.8	51,202.5	0.0	51,202.5
10 Non-ferrous smelting	2,043.0	2,311.6	656.5	2,876.8	7,887.9	0.0	7,887.9
11 Motor vehicles	303.1	1,511.7	762.8	162.2	2,739.8	0.0	2,739.8
12 Refineries	716.0	3,583.8	5,346.2	11,505.2	21,151.3	15,379.0	36,530.3
13 Chemicals	250.7	10,832.5	2,634.8	1,309.6	15,027.7	0.0	15,027.7
14 Other manufacturing	4,543.5	6,836.3	13,689.4	3,154.3	28,223.5	39,389.0	67,612.5
15 Electric utilities	278,635.9	1,513.4	9,097.8	6,505.0	295,752.1	0.0	295,752.1
16 Transportation	368.6	6,394.5	381,922.3	4,895.5	393,580.9	0.0	393,580.9
17 Services	1,308.4	17,894.8	293,245.2	8,405.9	320,854.3	0.0	320,854.3
Residential	1,086.9	25,397.9	333,876.3	12,250.4	372,611.5	-	372,611.5
Exogenous[c]	-	-	-	-	-	21,187.0	21,187.0
Total	338,069.1	98,168.8	1,305,371.7	70,806.7	1,812,416.3	155,761.0	1,968,177.3

Notes:
[a] Motor gasoline, diesel fuel oil, aviation gasoline and aviation turbo fuel.
[b] Petroleum coke, kerosene, light fuel oil and heavy fuel oil.
[c] Fuelwood combustion, private power plants and waste incineration.

Table B2

Canadian Total Hydrocarbon Emissions in 1985
(tonnes)

Model category	Emissions from Fuel Combustion					Industrial Process Emissions	Total
	Coal & Coke	Natural Gas	Motive Fuels[a]	Non-Motive Fuels[b]	Subtotal		
1 Agriculture	2,821.5	80.5	42,183.0	100.8	45,185.7	0.0	45,185.7
2 Fishing	0.0	1.2	6,770.8	1.7	6,773.7	0.0	6,773.7
3 Forestry	0.0	1.4	4,120.1	13.4	4,134.9	105,910.0	110,044.9
4 Non-coal mining	6.9	105.5	10,734.9	80.1	10,927.4	0.0	10,927.4
5 Coal mining	2.5	16.0	995.2	0.0	1,013.7	261,540.0	262,553.7
6 Crude oil & natural gas	0.0	49.5	11,671.0	0.0	11,720.5	27,309.0	39,029.5
7 Light manufacturing	0.4	279.0	6,952.0	37.6	7,268.9	0.0	7,268.9
8 Pulp & paper	20.2	252.0	3,537.8	260.7	4,070.7	96,047.0	100,117.7
9 Iron & steel	384.4	151.5	288.2	33.6	857.7	0.0	857.7
10 Non-ferrous smelting	17.5	94.9	151.3	67.1	330.8	0.0	330.8
11 Motor vehicles	2.6	62.1	878.2	3.5	946.3	0.0	946.3
12 Refineries	6.1	147.2	489.5	189.3	832.1	175,847.0	176,679.1
13 Chemicals	2.1	444.8	822.9	30.6	1,300.4	69,022.0	70,322.4
14 Other manufacturing	38.9	280.6	3,765.8	38.1	4,123.5	32,193.0	36,316.5
15 Electrical utilities	2,388.3	62.1	1,257.3	149.8	3,857.5	0.0	3,857.5
16 Transportation	3.2	261.1	78,731.1	114.2	79,109.6	0.0	79,109.6
17 Services	7,850.3	1,429.2	279,841.6	239.4	289,360.4	0.0	289,360.4
Residential	6,521.6	2,022.1	438,104.8	1,600.1	448,248.6	-	448,248.6
Exogenous[c]	-	-	-	-	-	628,185.0	628,185.0
Total	20,066.5	5,740.6	891,295.5	2,960.0	920,062.7	1,396,053.0	2,316,115.7

Notes:
[a] Motor gasoline, diesel fuel oil, aviation gasoline and aviation turbo fuel.
[b] Petroleum coke, kerosene, light fuel oil and heavy fuel oil.
[c] Fuelwood combustion, private power plants, tire wear, waste incineration, structural fires, dry cleaning, surface coatings, and general solvent use.

Table B3

Canadian Volatile Organic Compound Emissions in 1985
(tonnes)

Model category	Emissions from Fuel Combustion					Industrial Process Emissions	Total
	Coal & Coke	Natural Gas	Motive Fuels[a]	Non-Motive Fuels[b]	Subtotal		
1 Agriculture	1,567.5	53.3	38,462.9	31.2	40,114.9	0.0	40,114.9
2 Fishing	0.0	0.6	6,093.7	1.0	6,095.3	0.0	6,095.3
3 Forestry	0.0	0.7	3,786.4	3.3	3,790.5	80,809.0	84,599.5
4 Non-coal mining	4.6	50.6	9,820.1	21.5	9,896.8	0.0	9,896.8
5 Coal mining	1.6	7.7	932.6	0.0	942.0	0.0	942.0
6 Crude oil & natural gas	0.0	24.1	10,737.6	0.0	10,761.7	15,020.0	25,781.7
7 Light manufacturing	0.3	133.6	6,342.5	11.9	6,488.3	0.0	6,488.3
8 Pulp & paper	13.5	120.6	3,322.0	57.6	3,513.6	69,259.0	72,772.6
9 Iron & steel	256.2	72.5	264.4	7.4	600.5	0.0	600.5
10 Non-ferrous smelting	11.7	45.4	138.8	14.8	210.7	0.0	210.7
11 Motor vehicles	1.7	29.7	791.6	1.0	824.0	0.0	824.0
12 Refineries	4.1	70.4	464.0	65.2	603.7	149,071.0	149,674.7
13 Chemicals	1.4	212.8	750.7	6.7	971.6	50,000.0	50,971.6
14 Other manufacturing	26.0	134.3	3,441.5	19.9	3,621.6	32,172.0	35,793.6
15 Electrical utilities	1,592.2	29.7	1,170.5	34.4	2,826.9	0.0	2,826.9
16 Transportation	2.1	125.6	70,838.1	25.2	70,991.0	0.0	70,991.0
17 Services	4,361.3	946.5	252,542.7	156.1	258,006.5	0.0	258,006.5
Residential	3,623.1	1,338.3	394,398.9	462.7	399,822.9	-	399,822.9
Exogenous[c]	-	-	-	-	-	623,661.0	623,661.0
Total	11,467.3	3,396.2	804,299.1	919.9	820,082.5	1,019,992.0	1,840,074.5

Notes:
[a] Motor gasoline, diesel fuel oil, aviation gasoline and aviation turbo fuel.
[b] Petroleum coke, kerosene, light fuel oil and heavy fuel oil.
[c] Fuelwood combustion, private power plants, tire wear, waste incineration, structural fires, dry cleaning, surface coatings, and general solvent use.

Table B4

Canadian Sulphur Oxide Emissions in 1985
(tonnes)

Model category	Emissions from Fuel Combustion					Industrial Process Emissions	Total
	Coal & Coke	Natural Gas	Motive Fuels[a]	Non-Motive Fuels[b]	Subtotal		
1 Agriculture	4,819.6	30.3	4,427.6	2,395.7	11,673.1	0.0	11,673.1
2 Fishing	0.0	0.2	561.9	292.5	854.7	0.0	854.7
3 Forestry	0.0	1.2	1,020.3	2,939.3	3,960.9	0.0	3,960.9
4 Non-coal mining	3,281.5	22.6	2,627.8	17,412.4	23,344.3	0.0	23,344.3
5 Coal mining	1,171.1	3.8	579.1	0.0	1,754.0	0.0	1,754.0
6 Crude oil & natural gas	0.0	44.5	3,770.6	0.0	3,815.2	458,001.0	461,816.2
7 Light manufacturing	188.8	39.9	1,150.3	7,946.9	9,326.0	0.0	9,326.0
8 Pulp & paper	9,599.2	31.9	1,695.4	58,498.7	69,825.3	64,025.0	133,850.3
9 Iron & steel	188,653.6	18.0	64.3	7,539.5	196,275.4	0.0	196,275.4
10 Non-ferrous smelting	8,309.2	13.0	34.3	15,063.8	23,420.3	1,771,532.0	1,794,952.3
11 Motor vehicles	1,232.8	7.8	31.9	751.8	2,024.2	0.0	2,024.2
12 Refineries	2,912.2	16.9	286.6	58,046.5	61,262.3	73,959.0	135,221.3
13 Chemicals	1,019.7	49.3	135.5	6,857.5	8,062.0	0.0	8,062.0
14 Other manufacturing	18,479.1	36.5	692.5	14,746.6	33,954.7	82,644.0	116,598.7
15 Electrical utilities	698,579.9	10.0	483.8	33,474.0	732,547.7	0.0	732,547.7
16 Transportation	1,499.2	90.0	27,874.4	25,634.7	55,098.4	0.0	55,098.4
17 Services	10,028.3	408.4	20,168.1	27,213.2	57,818.0	0.0	57,818.0
Residential	11,140.0	362.2	10,485.3	25,277.8	47,265.4	-	47,265.4
Exogenous[c]	-	-	-	-	-	6,985.0	6,985.0
Total	960,914.2	1,186.6	76,089.8	304,090.9	1,342,281.6	2,457,146.0	3,799,427.6

Notes:
[a] Motor gasoline, diesel fuel oil, aviation gasoline and aviation turbo fuel.
[b] Petroleum coke, kerosene, light fuel oil and heavy fuel oil.
[c] Fuelwood combustion, private power plants and waste incineration.

Table B5

Canadian Carbon Dioxide Emissions in 1985
(kilotonnes)

Model category	Emissions from Fuel Combustion					Industrial Process Emissions	Total
	Coal & Coke	Natural Gas	Motive Fuels[a]	Non-Motive Fuels[b]	Subtotal		
1 Agriculture	796.3	1,233.6	6,657.9	978.1	9,665.9	0.0	9,665.9
2 Fishing	0.0	24.7	937.2	118.1	1,080.1	0.0	1,080.1
3 Forestry	0.0	31.8	1,131.8	306.2	1,469.8	15,712.3	17,182.1
4 Non-coal mining	292.8	2,189.8	3,026.6	2,037.7	7,546.9	0.0	7,546.9
5 Coal mining	104.5	333.5	549.0	0.0	987.0	0.0	987.0
6 Crude oil & natural gas	0.0	1,112.0	3,985.6	0.0	5,097.6	0.0	5,097.6
7 Light manufacturing	16.8	5,742.9	1,460.1	1,190.8	8,410.7	0.0	8,410.7
8 Pulp & paper	856.5	5,176.5	1,616.6	5,053.2	12,702.8	39,984.8	52,687.6
9 Iron & steel	17,080.6	3,110.1	73.5	651.3	20,915.5	0.0	20,915.5
10 Non-ferrous smelting	741.4	1,951.2	39.1	1,301.2	4,032.9	0.0	4,032.9
11 Motor vehicles	110.0	1,274.6	95.5	94.3	1,574.3	0.0	1,574.3
12 Refineries	259.8	3,018.8	265.4	4,929.6	8,473.6	0.0	8,473.6
13 Chemicals	91.0	9,120.8	172.2	592.4	9,976.3	4,045.6	14,021.9
14 Other manufacturing	1,648.8	5,767.9	851.7	1,496.2	9,764.6	6,284.8	16,049.4
15 Electric utilities	84,667.5	1,280.4	480.8	3,073.3	89,502.0	0.0	89,502.0
16 Transportation	133.8	5,506.3	27,102.6	2,214.4	34,957.0	0.0	34,957.0
17 Services	2,215.7	21,693.2	36,816.7	7,285.2	68,010.9	0.0	68,010.9
Residential	1,840.7	30,346.6	43,363.3	15,087.4	90,638.1	-	90,638.1
Exogenous[c]	-	-	-	-	-	10,480.0	10,480.0
Total	110,856.1	98,914.9	128,625.8	46,409.4	384,806.2	76,507.5	461,313.6

Notes:
[a] Motor gasoline, diesel fuel oil, aviation gasoline and aviation turbo fuel.
[b] Petroleum coke, kerosene, light fuel oil and heavy fuel oil.
[c] Fuelwood combustion, and municipal and industrial waste incineration.

Table B6

Comparison of Environment Model and DOE Emissions Data for 1985

	Nitrogen Oxides (tonnes)	Total Hydro-carbons (tonnes)	Volatile Organic Compounds (tonnes)	Sulphur Oxides (tonnes)	Carbon Dioxide (kilotonnes)
1. Environment Model					
Fossil Fuel Combustion	1,812,416.3	920,062.7	820,082.5	1,342,281.6	384,806.2
Industrial Processes	155,761.0	1,396,053.0	1,019,992.0	2,457,146.0	76,507.5
Total	1,968,177.3	2,316,115.7	1,840,074.5	3,799,427.6	461,313.6
2. Environment Canada					
Fossil Fuel Combustion	1,756,900.0	953,266.0	804,508.0	1,106,258.0	394,419.3
Industrial Processes	155,761.0	1,395,900.0	1,019,839.0	2,583,740.0	76,507.5
Total	1,912,661.0	2,349,166.0	1,824,347.0	3,689,998.0	470,926.8
3. Percentage Difference Between Environment Model and DOE Results					
Fossil Fuel Combustion	3.2	-3.5	1.9	21.3	-2.4
Industrial Processes	0.0	0.0	0.0	-4.9	0.0
Total	2.9	-1.4	0.9	3.0	-2.0

B.3 Abatement Costs

This section presents estimates of unit abatement costs and removal efficiencies for several technologies available to control emissions of common air pollutants. These estimates were gathered from a number of sources and adjusted to render them, to the greatest extent possible, consistent with each other.

Estimates of capital costs of control of each pollutant were converted to an annual basis by multiplying by a user cost of capital. This approach differs from that used in most engineering cost studies, which tends to divide the total capital cost (or the discounted present value of capital and operating costs) by the total reduction in emissions over the expected life of the asset. While it seems intuitively reasonable, the latter approach will underestimate true costs because it excludes the interest on capital costs and taxes on corporate income that must be paid by the firm if it undertakes the investment. Consequently, the estimates reported here tend to be higher than comparable figures found in other studies.

(i) Sulphur dioxide[34]

For SO_2 emissions from fuel combustion, estimates for wet flue-gas desulphurization (FGD) applied to industrial boilers and conventional thermal power plants were used. The primary source for capital costs (expressed in dollars per kilowatt capacity) and removal efficiency was the U.S. National Acid Precipitation Assessment Program (NAPAP, 1989). These figures were then converted to unit abatement costs (expressed in dollars per tonne SO_2 removed) to reflect differences in base-period fossil fuel use, emission factors, capacity utilization factors and industrial user costs of capital.

For industrial boilers, these transformations were fairly simple, due to the paucity of available data on boilers in Canada. Unit costs reported by NAPAP for sodium FGD on mid-sized (44 MW) coal-fired and oil-fired boilers were aggregated according to industries' 1985 fuel input shares, and converted to 1985 Canadian dollars. These

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[34] Firm/industry by province target reductions in SOx emissions between 1980 and 1994, as set out in the federal-provincial Acid Rain Control Program, are listed in table B7.

estimates, which assume a capacity factor of 80 per cent, are presented in table B8, together with comparable figures for the lime spray drying process.

For electric power plants, more detailed information was gathered, since they are a far larger source of SO_2 emissions and tend to spend more on emission control. Moreover, since capacity factors vary greatly among generating stations, calculated unit costs depend crucially on which plants are assumed to invest in abatement. Consequently, data on capacity factors for all utilities' thermal plants were gathered through direct communication with the utilities. These figures, together with estimates of average sulphur contents of fuels in each province, energy conversion efficiencies and nameplate plant capacities were used to convert capital cost estimates for limestone wet FGD from NAPAP (1989: 4-53) to unit abatement costs for each plant. The same procedure was followed to apply NAPAP's estimates of furnace sorbent injection capital costs.

Plant-level data were then aggregated to a single unit cost and removal efficiency under different scenarios regarding the extent of investment in the technology. In our base-case scenario, we assume that FGD would be applied to all plants in the seven eastern provinces fired by bituminous coal and heavy oil that have average capacity factors greater than 40 per cent. We estimate this would generate a maximum 76 per cent reduction in SO_2 emissions at an average unit cost of about $1400/tonne removed. Such a reduction far exceeds the 48 per cent reduction by utilities called for in the Canadian Acid Rain Control Program, and so almost certainly overestimates the cost of achieving current emissions targets. Hence we calculated estimates of the least-cost combination of investments that would yield approximately a 48 per cent reduction in total utility emissions. These results, together with estimates for other scenarios, are presented in table B9.

Simpler techniques were used to estimate the cost of abatement for non-ferrous smelting and refining. Since it seems that control regulations will apply to a relatively small number of establishments in Canada, it is less likely that *ex ante* costs estimates (such as those available from the NAPAP report) will provide an accurate indication of true costs. Instead the estimated unit cost is based on approximate capital costs and emission reductions for a number of large nickel, copper and zinc producers, which were provided

by Environment Canada. The estimated cost is $85 per tonne of SO_2 removed from industrial processes, and the maximum achievable reduction is 57 per cent.

(ii) Nitrogen oxides

Similar methods were used to estimate the costs of abating NO_x emissions. For industrial boilers, unit costs for low-NO_x burners (LNB) and selective catalytic reduction (SCR) were taken from Environment Canada (1990b), and adjusted to reflect an average capacity factor of 80 per cent and a user cost of capital of 15 per cent. These costs are provided in table B10.

For electric utilities, capital cost estimates were again drawn from NAPAP (1989) and converted to unit costs using other information on capacity factors and fuel use at Canadian power plants. Unit costs for various least-cost control scenarios are presented in table B11.

No estimates were found of costs of controlling NO_x emissions from industrial processes.

(iii) Other air pollutants

A small number of estimates were found of costs of technologies for the control of emissions of methane and volatile organic compounds. These estimates have been used virtually without adjustment in the model.

For volatile organic compounds, cost estimates are provided in Environment Canada (1990c) for abatement technologies applicable to crude oil, petroleum refining and chemical production industries. Emissions associated with crude oil occur during the extraction, storage and transfer of the product, and are controlled essentially by plugging leaks. Both fugitive and process-related emissions occur during petroleum refining, and can be controlled through a variety of techniques. Emissions from chemicals and plastics production are chiefly process-related, and would be most cheaply controlled by flaring vent gases. Estimates of unit costs for each of the three sectors are provided in table B12.

Control technologies for methane emissions were surveyed by DPA Group (1989). Quantitative estimates of costs were, however, available only for control of fugitive emissions from coal mines. These figures are also included in table B12.

It was not possible to adjust the figures for either VOCs or methane to account for the user cost of capital to industries. Consequently, actual economic costs can be expected to be considerably higher.

Table B7

Acid Rain Control Program:
Industry Targets by Province

	1980 SOx Emissions (kilotonnes)	1994 SOx Emissions (kilotonnes)	Percentage Reduction
Manitoba	**738**	**550**	**25**
HBMS	293	220	25
Inco	414	220	44
Other	31	110	-
Ontario	**2194**	**885**	**60**
Inco	1155	265	77
Falconbridge	154	100	35
Algoma Steel (Wawa)	161	125	22
Electricity	452	175	61
Other	272	220	19
Quebec	**1085**	**600**	**45**
Noranda	552	275	50
Gaspé	91	65	29
Other	442	260	41
New Brunswick	**215**	**185**	**14**
Electricity	122	130	-
Other	93	55	41
Nova Scotia	**219**	**207**	**5**
Electricity	125	160	-
Other	94	47	50
Prince Edward Island	**6**	**5**	**17**
Newfoundland	**59**	**45**	**24**
Total	**4516**	**2477**	**45**

Table B8

Sulphur Oxide Abatement Technologies for Industrial Boilers: Cost and Effectiveness by Industry

Industry	Sodium wet FGD		Lime spray drying	
	Unit Capital Cost (1985 $ per tonne of SOx)	Maximum reduction (per cent)	Unit Capital Cost (1985 $ per tonne of SOx)	Maximum reduction (per cent)
Light manufacturing	1028.9	89	2263.2	5
Pulp & paper	1020.5	90	2263.2	15
Iron & steel	1026.1	90	2263.2	9
Refineries	1001.5	90	2263.2	39
Chemicals	1033.2	89	n.a.	0
Other manufacturing	971.4	90	2263.2	75
Services	n.a.	0	n.a.	0

Note: n.a. = not applicable

Table B9

Costs of Sulphur Oxide Control Technologies for Electric Utilities

Control strategies	Wet limestone scrubbing		Furnace sorbent injection	
	Unit Capital Cost (1985 $ per tonne of SOx)	Maximum Reduction (per cent)	Unit Capital Cost (1985 $ per tonne of SOx)	Maximum Reduction (per cent)
1. All bituminous coal-fired plants	1435	76.1	458	59.2
2. #1 with capacity factor greater than 40%	945	70.4	304	54.8
3. All bituminous & heavy oil-fired plants with capacity factor greater than 40%	1003	80.7	323	62.8
4. Least-cost combination of all types of plants for 48% reduction in emissions	409	48.0	n.a.	n.a.

Note: n.a. = not applicable

Table B10

Nitrogen Oxide Abatement Technologies for Industrial Boilers: Cost and Effectiveness by Industry

Industry	Low-NOx burners		Selective catalytic reduction	
	Unit Capital Cost (1985 $ per tonne of NOx)	Maximum reduction (per cent)	Unit Capital Cost (1985 $ per tonne of NOx)	Maximum reduction (per cent)
Light manufacturing	172.7	46	2674.5	90
Pulp & paper	148.0	42	2674.5	90
Iron & steel	168.9	46	2674.5	90
Refineries	156.6	46	2674.5	90
Chemicals	170.1	46	2674.5	90
Other manufacturing	162.0	47	2674.5	90
Services	147.2	41	2674.5	90

Table B11

Costs of Nitrogen Oxide Control Technologies for Electric Utilities

	Unit Capital Cost (1985 $ per tonne of NOx)	Maximum Reduction (per cent)
Low-NOx burners:		
1. Least-cost small reduction	145	26.6
2. Least-cost large reduction	155	29.1
Selective catalytic reduction:		
3. Least-cost small reduction	1082	23.0
4. Least-cost large reduction	1434	55.1

Table B12

Costs of Other Emission Control Technologies: Methane and Volatile Organic Compounds

	Unit Capital Cost (1985 $ per tonne)	Maximum Reduction (per cent)
Methane emissions control:		
Coal mining	36	50
VOC emissions control:		
Crude oil and natural gas	931	70
Refineries	177	84
Chemicals	369	90

B.4 Elasticities

In order to calibrate the environment model based on the input-output and international trade data, and then to conduct simulations of various environmental policy measures, the elasticity-of-substitution parameters of the CES functions employed in consumption, intermediate-materials aggregates and value-added aggregates first need to be specified. These parameter values are derived from estimates of either own-price elasticities of demand or elasticities of supply.

The CES nesting structure adopted for consumption yields the following relationship between elasticities of substitution ($\varepsilon^{k,s}$) and uncompensated own-price elasticities of demand ($\eta^{j,s+1}$) at each level of nesting:

$$(B1) \quad \eta^{j,s+1} = \sum_{s} \varepsilon^{k,s} \left(HC^{j,s} - HC^{j,s+1}\right) - HC^{j,1} \qquad \begin{array}{l} s = 1,\ldots,5 \\ k \in C_s \\ j \in C_{s+1} \end{array}$$

where $HC^{j,s} = (P^{j,s+1}\, Z^{j,s+1}) \,/\, (P^{k,s}\, Z^{k,s})$, $HC^{j,s}$ is the expenditure share of commodity or commodity aggregate $j \in C_{s+1}$ in nesting level s in consumption, $P^{k,s}$ is the market price of commodity aggregate k in nesting level s, and $P^{j,s+1}(s=5) = P_j$, $j \in C$, where P_j is the consumer price of commodity j.

Similarly, the relationship between elasticities of substitution ($\sigma_i^{k,m}$) and compensated own-price elasticities of demand ($\eta_i^{j,m+1}$) at each level of nesting for the intermediate-materials aggregates can be formulated as follows:

$$(B2) \quad \eta_i^{j,m+1} = \sum_{m} \sigma_i^{k,m} \left(HI_i^{j,m} - HI_i^{j,m+1}\right) \qquad \begin{array}{l} i \in I \\ m = 2,\ldots,6 \\ k \in G_m \\ j \in G_{m+1} \end{array}$$

where $HI_i^{j,m} = (q_i^{j,m+1}\, X_i^{j,m+1}) \,/\, (q_i^{k,m}\, X_i^{k,m})$, $HI_i^{j,m}$ is the cost share of commodity or materials aggregate j in nesting level m.

The CES nesting structure in the value-added aggregates differentiates between resource and electric utilities industries, on the one hand, and manufacturing and service industries, on the other. The former industries employ a fixed, sector-specific resource factor in their production processes; the latter do not. For the resource and electric utility industries, a relationship is established in the model between the elasticity of substitution in value added ($\rho_i^{d,n}$) and the elasticity of supply for industry i (η_i^s), rather than between elasticities of substitution in value added and demand for the fixed factor. This relationship is given as:

$$(B3) \quad \eta_i^s = \rho_i^{d,n} \left[1 - \left(HV_i^{n+1,y} / HV_i^{n,y}\right)\right] / HV_i^{n+1,y} \qquad \begin{array}{l} i \in I \\ n = 2 \\ d \in F_n \end{array}$$

where $HV_i^{n,y}$ and $HV_i^{n+1,y}$ are cost shares of value added and the fixed factor, respectively, in revenue of industry i. A relationship is also established between the elasticity of substitution ($\rho_i^{d,n}$) and compensated own-price elasticities of demand ($\eta_i^{j,n+1}$) for capital or labour in the resource and electric utilities industries.

$$(B4) \quad \eta_i^{j,n+1} = \sum_n \rho_i^{d,n} \left(HV_i^{j,n} - HV_i^{j,n+1}\right) \qquad \begin{array}{l} i \in I \\ n = 3;\ 2 \\ d \in F_n \\ j \in F_{n+1} \end{array}$$

where $HV_i^{j,n} = (w_i^{j,n+1} V_i^{j,n+1}) / (w_i^{d,n} V_i^{d,n})$, $HV_i^{j,n}$ is the cost share of primary factor or value-added aggregate j in nesting level n. For manufacturing and service industries in the model, the relationship between elasticities of substitution and demand is the same as shown in equation (B4) except that n = 2.

Since energy demand elasticities tend to be important determinants of the results of environmental policy simulations, substitution elasticities employed in consumption and intermediate-materials aggregates in the environment model are based on own-price elasticities of energy demand, namely, stationary energy, electricity, motive fuels, and natural gas. Energy demand elasticities are, for the most part, estimates derived from

EMR's IFSD model.[35] They were calculated by increasing reference-case energy prices by one per cent to determine the resulting percentage changes in energy demands over a 15-year period. Own-price elasticity estimates in intermediate-materials aggregates and in consumption aggregates are listed in table B13.

For most environmental policy simulations, the most important determinant of model results is the elasticity of stationary energy demand. Consequently, the single IFSD elasticity estimate of -0.29 obtained from the IFSD model for the industrial sector as a whole was disaggregated for each of the manufacturing industries in the environment model, except the iron and steel industry, based on information in Taher *et al* (1985). For electricity and natural-gas aggregates in the 16 non-service industries, the model generally replicates IFSD's elasticity parameters for the industrial sector (-0.49 for electricity and -0.82 for gas).[36] For the service industry, IFSD's elasticities for the commercial sector (-0.36 for electricity and -1.05 for natural gas) were used. For motive fuels, a weighted-average own-price elasticity for each of the industrial categories of the model and for final demand was calculated based on IFSD estimates of -1.02 for gasoline and -0.57 for diesel fuel, and 1985 demands for each of these fuels by industrial sector.

Table B14 provides information on elasticities of supply and elasticities of consumer demand for imports and exports employed in the environment model. The supply elasticity for crude oil and natural gas was obtained from Thirsk and Wright (1977). Supply elasticity estimates for the remaining resource and electric utilities industries were not forthcoming in a survey of the economics literature; consequently, reasonable values for these elasticities were chosen based on the estimate for crude oil and natural gas. For the Armington goods-producing industries of the model, price elasticities of demand for Canada are obtained from Létourneau and Lester (1988); price elasticities of demand for exports are derived from U.S. import price elasticities reported by Almon *et al* (1975).

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[35] See EMR (1990).

[36] Four industries -- coal mines, oil and gas extraction, refineries and chemical producers -- are exceptions to this rule. For obvious reasons, these sectors are believed to have limited substitution possibilities among coal, crude oil and natural gas, and refined petroleum products; the fourth level substitution elasticity has therefore been set near zero for these industries. For the same reason, substitution elasticity values for the electric utilities and iron and steel industries are set near zero for stationary energy, electricity and natural gas aggregates.

Table B13

Own-Price Elasticities of Demand in Intermediate-Materials Aggregates and Consumption[a]

Model Category	Stationary Energy	Electricity	Motive Fuels	Natural Gas
Agriculture	-0.79	-1.08	-0.72	-1.32
Fishing	-0.29	-0.49	-0.52	-0.76[b]
Forestry	-0.29	-0.49	-0.60	-0.82
Non-coal mining	-0.29	-0.49	-0.61	-0.82
Coal mining	-0.29	-0.49	-0.44	-0.59[b]
Oil & gas production	-0.29	-0.49	-0.64	-0.33[b]
Light manufacturing	-0.34	-0.49	-0.73	-0.82
Pulp & paper	-0.27	-0.49	-0.59	-0.82
Iron & steel	-0.17[b]	-0.19[b]	-0.66	-0.19[b]
Non-ferrous smelting	-0.39	-0.49	-0.69	-0.82
Motor vehicles	-0.17	-0.49	-0.96	-0.82
Petroleum refining	-0.04	-0.49	-0.57	-0.05[b]
Chemicals	-0.51	-0.49	-0.64	-0.35[b]
Other manufacturing	-0.17	-0.49	-0.71	-0.82
Electric utilities	-0.07[b]	-0.15[b]	-0.59	-0.15[b]
Transport services	-0.08	-0.36	-0.50	-0.37[b]
Other services	-0.08	-0.36	-0.85	-1.05
Consumer demands	-0.82	-1.10	-1.01	-1.32

Notes:
[a] Own-price elasticity: percentage change in quantity given a one per cent change in own price.
[b] Imposed *a priori* rather than calculated from empirical estimates.

Table B14

Own-Price Elasticities of Supply and of Demand for Imports and Exports[a]

Model Category	Fixed Factor	Supply Elasticity	Homo-geneous Product	Import Elasticity[b]	Export Elasticity[c]
Agriculture	yes	1.0[d]	no	-2.4	-3.6
Fishing	yes	1.0[d]	yes	-	-
Forestry	yes	1.5[d]	yes	-	-
Non-coal mining	yes	1.5[d]	yes	-	-
Coal mining	yes	1.5[d]	no	-1.0	-3.4
Oil & gas production	yes	1.5	yes	-	-
Light manufacturing	no	-	no	-2.2	-4.7
Pulp & paper	no	-	no	-2.3	-3.3
Iron & steel	no	-	no	-2.2	-4.8
Non-ferrous smelting	no	-	no	-1.9	-3.3
Motor vehicles	no	-	no	-1.5	-4.3
Petroleum refining	no	-	no	-2.1	-4.8
Chemicals	no	-	no	-1.4	-4.6
Other manufacturing	no	-	no	-1.7	-4.7
Electric utilities	yes	1.5[d]	no	-2.5	-4.2
Transport services	no	-	no	-2.5	-2.5
Other services	no	-	no	-0.9	-4.6

Notes: - Not applicable.

[a] Own-price elasticity: percentage change in quantity given a one per cent change in own price.

[b] Canadian consumer demand for imports from the U.S. and ROW.

[c] U.S. consumer demand for Canadian exports.

[d] Imposed *a priori* rather than calculated from empirical estimates.

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